A Review of Micro-EDM

S. Mahendran, R. Devarajan, T. Nagarajan, and A. Majdi

***Abstract*-There is a huge demand in the production of microstructures by a non-traditional method which is known as Micro-EDM. Micro-EDM process is based on the thermoelectric energy between the workpiece and an electrode. Micro-EDM is a newly developed method to produce micro-parts which in the range of 50 µm -100 µm. Micro-EDM is an efficient machining process for the fabrication of a micro-metal hole with various advantages resulting from its characteristics of non-contact and thermal process. A pulse discharges occur in a small gap between the work piece and the electrode and at the same time removes the unwanted material from the parent metal through the process of melting and vaporization. This paper describes the characteristics, parameters of material removal rate and the tool wear rate that are essential in the Micro-EDM process.**

***Index Terms* - Micro-EDM, EDM, Micromachining, Non-Conventional Machining Process**

1. INTRODUCTION

Micro Electrical Discharge machining is quite similar with the principals of Electrical Discharge Machining. According to Z. Katz and C.J Tibbles from the article "Analysis of micro-scale EDM process" states that Electro discharge machining (EDM) is a thermal process that uses electrical discharges to erode electrically conductive materials. EDM has a high capability of machining the accurate cavities of dies and molds (H. Zarepur, A. Fadaei Tehrani, D. Karimi, S. Amini, 2007). EDM is an effective technique in the production of micro components that are smaller than 100µm. EDM is a contactless process that exerts every small force on both the work piece and tool electrode.

EDM is a process that provides an alternative method to produce microstructures. It is also states that the micro EDM is similar to the principal of macro EDM where the process mechanism is based on an electro-thermal process that relies on a discharge through a dielectric in order to supply heat to the surface of the work piece. The current causes the heating of the dielectric, the work piece, and the electrode. The dielectric forms a channel of partially ionized gas. The discharge power is dissipated in the plasma channel with amount between 2% and 10%. The channel acts as a heat source on the surface of the work piece. Then the work piece is locally heated beyond its melting point and removed after the material ejected solidifies within the cooler dielectric medium. The significant difference between micro and macro EDM is the plasma channel radius (Diameter). In macro EDM the plasma size is larger by several orders of magnitude than the plasma channel radius. The size of the plasma can be changed by the pulse duration because the channel radius increases as the time increases. If the pulse duration time allows the channel to expand until it is larger than the electrode diameter, the rate of its expansion will change.

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2. PRINCIPALS OF MICRO EDM

Based on the journal Rapid Biocompatible Micro Device Fabrication by Micro Electro-Discharge Machining by M. Murali & S. H. Yeo. Micro EDM is based on a simple theory, when two electrodes is separated by a dielectric medium, come closer to each other, the dielectric medium that is initially non conductive breaks down and becomes conductive. During this period sparks will be generated between the electrodes. The thermal energy released will be used for the material removal by melting and evaporation. By precisely controlling the amount energy released, it is possible to machine micro features on any electrically conductive material.

Based on "Advancing EDM through Fundamental Insight into the Process" journal by M. Kunieda(Tokyo University of Agriculture and Technology, Japan), B. Lauwers (Katholieke Universiteit Leuven, Belgium), K.P. Rajukar (University of Nebraska-Lincoln, USA), B.M Schumacher (University of Applied Science St Gallen, Switzerland) explains the basic principle of EDM. In the gap filled of insulating medium most preferable a dielectric liquid such as hydrocarbon oil or de-ionized water between the tool and electrode occurs the discharging of the pulsed arc. The insulating medium is to avoid the electrolysis effects on the electrodes during the EDM process. The electrode shape is copied with an offset equal to the gap size and the liquid will be selected to minimize the gap in order to obtain precise machining. To make sure it is safe, a certain gap width is needed to avoid short circuiting especially for electrodes that are sensitive to vibration or deformation is used. Initially, a high voltage current is needed to discharge in order to overcome the dielectric breakdown strength of the small gap. Formed between the electrodes is a channel of plasma (ionized and electrically conductive gas with high temperature) and it will develops further depends on the discharge durations.

Discharge occurs at high frequencies between 10^3 and 10^6 hertz since the metal removal per discharge is very small. For every pulse, discharge occurs at a particular location where the electrode materials are evaporated or ejected in the molten phase then a small crater is generated both on the tool electrode and workpiece surfaces. The removed material are then cooled and re-solidified in the dielectric liquid forming

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several hundreds of spherical debris particles which will be flushed away from the gap by the dielectric flow.

At the end of the discharge duration, the temperature of the plasma and the electrode surfaces that is in contact of the plasma rapidly drops, resulting in the recombination of ions and electrons also the recovery of the dielectric breakdown strength. To obtain stable condition in EDM, it is important for the next pulse discharge occur at a spot distanced sufficiently far from the previous discharge location. This is because the previous location will result in having a small gap and it is contaminated with debris particles which may weaken the dielectric breakdown strength of the liquid. The time interval for the next discharge pulse should be long so that the plasma that is generated by the previous discharge can be fully de-ionized and the dielectric breakdown strength around the previous discharge location can be recovered by the time the next voltage charge is applied. If happens that the discharges occurs at the same location, resulting in thermal overheating and non-uniform erosion of the workpiece.

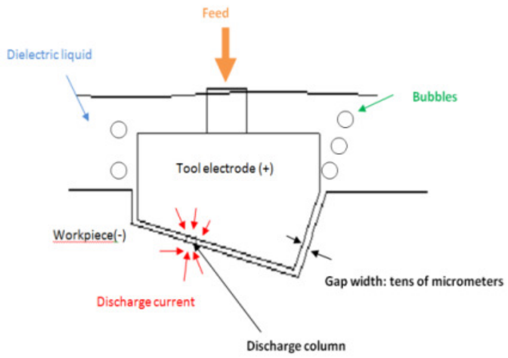

Figure 1: Concept of EDM

3.0 TYPES OF EDM PROCESS

3.1 SINKING EDM

Adapted from the article "Advancing EDM through Fundamental Insight into the Process" by M. Kunieda(Tokyo University of Agriculture and Technology, Japan), B. Lauwers (Katholieke Universiteit Leuven, Belgium), K.P. Rajukar (University of Nebraska-Lincoln, USA), B.M Schumacher (University of Applied Science St Gallen, Switzerland). The sinking electrical discharge machining is as shown in Figure 2. The workpiece can be formed either by replication of a shaped tool electrode or by 3-Dimensional movement of a simple electrode similar to milling or we can use the combination of both the methods. Normally we use copper or graphite as the electrode material. The numerical control monitors the gap conditions and synchronously controls the different axes and the pulse generator. The dielectric liquid is filtrated to remove debris particles and decomposition products. Hydrocarbons dielectric is normally used since the surface roughness is better and tool electrode wear is lower compared to the de-ionized water.

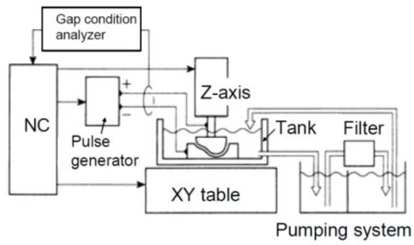

Figure 2: Sinking Electrical Discharge Machining

3.2 WIRE EDM

In the figure below outlines the wire electrical discharge machining (WEDM method) which is taken from the article "Advancing EDM through Fundamental Insight into the Process" by M. Kunieda, B. Lauwers, K.P. Rajukar, B.M Schumacher. Wire electrode methods can cut complicated shapes like a wire sawing machine. Normally the wire electrode is brass wire or coated steel wires but in case of thin wires tungsten or molybdenum wires are used. Since we can change the orientation of the wire by controlling the horizontal position of the upper wire guide relative to the lower guide all types of surfaces can be cut. Discharge current with a high peak value over a short duration of time are used, both the upper and lower feeding brush are supplied with current to obtain a quick rise in the discharge current by reducing the inductance in order to avoid breakage due to Joule heating. To reduce vibration and deflection tension is applied to the wire resulting in deteriorated cutting accuracies. Water is the most often used as the dielectric liquid but its specific electrical conductivity should be decreased using de-ionizing resins to avoid electrolysis and to keep high open voltage.

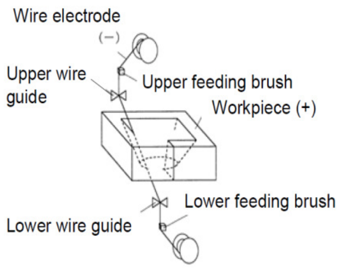

Figure 3: Wire Electrical Discharge Machining

4. DIELECTRIC FLUIDS

In micro electrical discharge (MEDM) machining the most important thing to ensure the efficiency of the feed is the dielectric fluids. In MEDM the dielectric fluid acts as a cutting medium to improve surface roughness, corrosion resistance and wear resistance. In most die-sinking process use kerosene as the dielectric fluid (Han-Min Chow, Lieh-Dai Yang, Chin-Tien Lin, Yuan Feng Chen, 2007). However there are a lot of dielectric fluids that can be replace to replace kerosene such as pure water (distilled water) because pure water has a high thermal conductivity, a low viscosity

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coefficient, and a high flowing rate. Pure water temperature is not affected by long working time, and this will improve the material removal rate (MRR).

Recent researches indicated that adding powder in EDM process will enhance MRR, therefore improving the surface roughness, corrosion resistance and wear resistance. Previous researchers (Yan, 1994, Chen, 1993) used kerosene added with aluminum powder as an EDM dielectric fluid and obtained a high material removal rate and improved surface roughness. Additives can improve the surface quality of workpiece quite effectively by increasing the material removal rate (MRR) and decreasing the tool wear rate especially in mid-finish machining and finish machining (Ming, He, 1995). Other than that, we can also use oil as the dielectric fluids which will affect the tool electrode wear where it depends on the significance of the pulse duration (Masonori Kunieda, Teruki Kobayashi, 2004)

Recently green manufacturing has become very important to all manufacturing industries, thus the use of pure water has been proved to have more good effect on the workpiece since water has a high thermal conductivity, a low viscosity coefficient, and a high flowing rate and pure water will not be affected by a long working time. Thus a constant high material removal rate will be obtained (Han-Min Chow, Lieh-Dai Yang, Chin-Tien Lin, Yuan Feng Chen, 2007).

5. MINIMUM MACHINABLE SIZE

Recently the demands for microscopic parts have increased and the research on Micro EDM is becoming more and more important. The minimum machinable diameter of micro rods obtained by EDM is about 5 μm at best. Thus more effort is needed to extend the limits of miniaturization in micro EDM. The factors that affect the limits is maybe because the electric discharge energy of each pulse discharge, this is a result of the discharge crater increases with increasing electric discharge energy(T. Kawakimi, M. Kunieda). However the limits of minimum machinable size are not decided only by the electric discharge energy. Residual stress that is caused by EDM results in distortion of micro workpieces (Spur, G., Uhlmann, Kruth).

6. TYPES OF POWER SUPPLY

In conventional EDM, the current level is high as well as the voltage required. As a result of high currents, the electrode gets locally melted and there is welding of the workpiece and electrode. There are also problems of stray arcing. Moreover, uncontrolled discharge cannot be allowed in micro-machining. Thus a different power supply is required for micro EDM. Pulsed DC power supply is a critical component for achieving the required parameters of accuracy, finish and size of micro holes by using EDM process. The purpose if the power supply is to convert the alternating current into a pulsed unidirectional direct current required to produce the spark and also the effectiveness of the EDM is determined by the type of power supply used.

6.1 ROTARY IMPULSE GENERATOR

This is the rotary impulse generator power supply where the voltage waveform is generated based on the DC motor principle, which it creates a sinusoidal wave pattern that is similar to rectification.

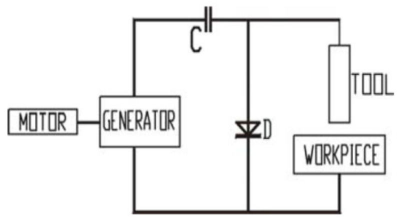

Figure 5: Rotary Impulse Generator (Aditya Shah, V. Prajapati, P. Patel, A. Pandey)

6.2 RELAXATION GENERATOR

Figure 6 is called the relaxation generator where the principal is based on the charging and discharging of the capacitor that is connected to the power supply. The type of wave that is generated by these arrangements is the saw tooth wave. In creating the spark, the capacitor is allowed to charge and then it is brought to contact with the workpiece and discharges.

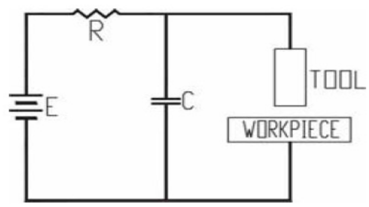

Figure 6: Relaxation Generator (A. Shah, V. Prajapati, P. Patel, A. Pandey)

6.3 PULSE GENERATOR

Solid state devices are used instead of capacitor and resistors in pulse generator. Replacing the capacitor a solid-state devices such as the transistor are used. They are toggled between of state and saturation state to generate rectangular pulse which swing between zero and supply voltage. The idea is to increase the production efficiency which it have higher production efficiency than the relaxation circuits.

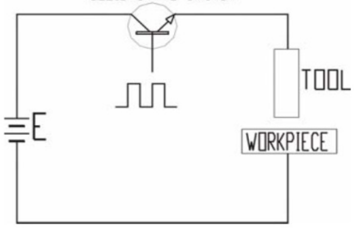

Figure 7: Pulse Generator (A. Shah, V. Prajapati, P. Patel, A. Pandey)

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7. EDM PROCESS PARAMETERS

In theory, we can say that the process parameters of EDM and the process parameters of Micro-EDM are quite similar. This is because the working principal is the same which that both of the machining uses Electric Discharge Machining where electrodes discharges pulses and cut away the metal with help of dielectric fluid for better machining accuracy. The dielectric fluid also acts as a lubricant to ensure the machining is accurate and running smooth. We can assume that the process parameters needed in EDM and micro-EDM is similar due to the similarity explained above. It is also states that the micro EDM is similar to the principal of macro EDM where the process mechanism is based on an electro-thermal process that relies on a discharge through a dielectric in order to supply heat to the surface of the work piece (H. Zarepur, A. Fadaei Tehrani, D. Karimi, S. Amini, 2007).

7.1 DISCHARGE VOLTAGE

The spark gap and the breakdown strength of the dielectric is related to the discharge voltage in EDM processes. Current will flow into the system and before it happen the open gap voltage increases until it has created a path that will go through the dielectric. The path that is mentioned before is called the ionization path. When the current is flowing, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and the workpiece (Sanjeev Kumar, Rupinder Singh). If we set the voltage to a high value then the gap will increase, increasing the gap will improve the flushing conditions and helps to stabilize the cut. The open circuit voltage also have an impact to the system, as we increase the open circuit voltage tool wear rate (TWR) and surface roughness increases because the field strength increases.

7.2 PEAK CURRENT

Peak current is known as the amount of power used in discharge machining which this parameter is measured in amperage and above all this is the most important parameter in EDM machining. During each on-time pulse, the current increases until it reaches a preset level which is express as the peak current. In roughing operations or cavities in large surface areas higher amperage is used. Using higher currents will definitely improve material removal rate (MRR) but it will give an impact on the surface finish and tool wear. Despite the machine cavity is a replica of tool electrode and excessive wear will hamper the accuracy of machining and as a result, all of the above statements is important in EDM. New improved electrode materials, especially graphite, can work on high currents without much damage (Ho and Newman, 2003).

7.3 PULSE DURATION AND PULSE INTERVAL

Expressed in units of microseconds the cycle has an on-time and off –time. On the on-time all the work is produced and as a result the duration of these pulses and the number of cycles per second are important. Metal removal is directly proportional to the amount of energy applied during the on-time (Singh et. al., 2005). The energy applied during the on-time controls the peak amperage and the length of the on-time. Pulse duration and pulse off-time is called pulse interval. If the pulse duration is longer, then more workpiece material will be melted away. Then, it will have a broader and deeper hole than using shorter pulse duration. Even though the hole has rough surface finish, the extended pulse duration will allow more heat sink into the workpiece and in the mean time it will spread which means the recast layer will be larger and the heat affected zone will be deeper.

However, exceeding the pulse duration will also have its benefits. Whereas, when the optimum pulse duration for each electrode and work material combination is exceeded, the material removal rate will start to decrease. The longer the duration will have effect on the wear of the work material where when the duration of the pulse is longer, then there will be a no-wear situation. But there are a certain limits for that point to be reached. But if that point is reached, increasing the duration will cause the electrode to grow from plating build-up. To complete the cycle sufficient pulse interval is needed before the next cycle can be started. Other than that, the pulse interval also affects the speed and the stability of the cut. From theory, the shorter the interval the faster the machining operation will be. But this will affect the workpiece material where it will not be swept away by the flow of the dielectric and as a result the fluid will not be de-ionized. As a result the next pulse will be unstable and hard to control. This unstable condition will cause erratic cycling and retraction of the advancing servo and this will slow down the cutting rate. At the same time, pulse interval must be greater than the de-ionization time to prevent continued sparking at one point (Fuller, 1996). In ideal conditions, each pulse creates a spark. However, it has been observed practically that many pulses fail if duration and interval are not properly set, causing loss of the machining accuracy and those pulses are called open pulses (Sanjeev Kumar, Rupinder Singh).

7.4 PULSE WAVEFORM

The normal pulse waveform that we always see is rectangle, but now new shapes have been developed. Pulse wave is a non-sinusoidal waveform that is similar to square wave. By using trapezoidal wave generators the relative tool wear can be reduced to a very low value. Other types of generators introduce an initial pulse of high voltage but low current and a few microseconds duration, before the main pulse, which facilitates ignition (Sanjeev Kumar, Rupinder Singh).

7.5 POLARITY

Polarity can be either positive or negative. The current will pass through the gap and create high temperature that will

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cause the material to evaporate at both the electrode spots. The plasma channel is made of ion and electron flows. Electrons have mass smaller than anions and as the electrons processes it shows quicker reaction, the anode material is worn out predominantly. As a result it causes minimum effect to the tool electrode and becomes important for finishing operations with a shorter on-time. While running long discharges the early electron process predominance changes to positron process which will result in high tool wear rate. Polarity is determined by experiments and is a matter if tool material, work material, current density and pulse length combinations. Modern power supplies insert an opposite polarity "swing pulse" at fixed intervals to prevent arcing (Sanjeev Kumar, Rupinder Singh). A typical ratio is 1 swing for every 15 standard pulses (Ho and Newman, 2003).

7.6 ELECTRODE GAP

The tool servo-mechanism is one of the most important in the efficient working of EDM process, and the servo-mechanism function is to control the working gap to the set value. An electro-mechanical and hydraulic systems are used and normally designed to respond to average gap voltage. In order to obtain good performance, gap stability and the reaction speed of the system needs to be account for where the presence of backlash is particularly undesirable. For the reaction speed, it must obtain a high speed so that it can respond to short circuits or even open gap circuits. Gap width is not measured directly, but can be inferred from the average gap voltage (Crookall and Heuvelman, 1971).

8. TYPE OF DIELECTRIC FLUSHING

A dielectric in EDM must have a basic characteristic of high dielectric strength and quick recoveries after breakdown also have an effective quenching and flushing ability. Tool wear rate and material removal rate is affected by the type of dielectric used and the method of its flushing. The use of hydrocarbon compounds and water are commonly used as dielectric fluids. But for de-ionized water is usually used for wire-EDM and high precision die-sinking because of its low viscosity and carbon free characteristics. The dielectric fluid is flushed through the spark gap to remove gaseous and solid debris during machining in order to maintain the temperature so that it is always below the flash point. A control feature that is commonly seen on many machines to facilitate chip removal is vibration or cyclic reciprocation of the servo tool electrode to create a hydraulic pumping action. Orbiting of the tool workpiece has also been found to assist flushing and improve machining conditions (Levy and Ferroni, 1975).

9. MATERIAL REMOVAL RATE (MRR)

Based from the journal "Influence of pulsed power conditions on the machining properties in micro-EDM" shows that the source energy of electro discharge between the tool electrode and the workpiece is an electric one which power can be determined by the supplied voltage and current. Thus, the electro discharge energy can be expressed as shown in Eq. (1).

$$E = VIT$$

In the pulse current, if time T is substituted to an intermittent one with frequency, Eq. (1) is expressed to the following

$$E_p = V_p I_p t_{on} \frac{1}{t_{on} + t_{off}}$$

Where;

V_p: Voltage of a single pulse, I_p: Current of a single pulse, t_{on}: pulse on-time, t_{off}: pulse off-time.

The equation for material removal rate can be produce by multiplication of machining property. Hence the expression can be written as Eq. (3):

$$MRR = \alpha V_p I_p t_{on} \frac{1}{t_{on} + t_{off}}$$

Where α is the removal constant of a material. This constant is the removal volume of a material per unit electric power.

From Eq. (3) the parameters of voltage, current and pulse On-time are proportional to the material removal rate. At the same time the frequency of the pulse is also proportional to the material removal rate, but the parameter is not perfectly independent of the pulse On-time. This is because the pulse Off-time is needed sufficiently, depending on the power of a single pulse.

The equation also indicates that a shorter duration is more advantageous than a longer one to make accurate machining under the same conditions. Since the removal rate is the same but the removal volume per pulse is smaller in the shorter pulse, if the ratio of pulse On-time to Off-time is the same.

10. TOOL WEAR RATE (TWR)

The ratio of amount of electrode to the amount of workpiece removal is defined as the wear ratio (Yao Yang Tsai, Takahisa Masuzawa). There are four methods that are known to evaluate the electrode wear ratio by means of measuring weight, shape, length, and total volume respectively. A common one is by calculating the volumetric wear ratio (υ). Usually we will measure the weight differences and transfer them into the volumes by the density of materials. However this method is unsuitable for micro-EDM because the weight change is so small making it difficult to measure it accurately. Therefore, it is important to measure and analyze removed material directly.

In Fig. 8 the change of electrode length and corner rounding is illustrated. In the figure the worn electrode can be divided into two parts which is V_B and V_C. V_B is the wear volume on bottom portion and V_C is the wear volumes of corner portion and V_C are assumed to be the volume of a cylinder of a revolution body, respectively, because a rotating electrode is used during machining.

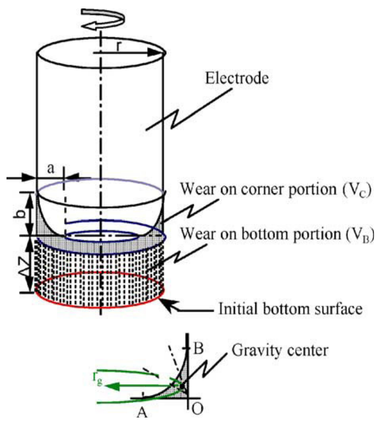

Figure 8: Wear volume of the electrode adapted from Y-Y. Tsai, T. Masuzawa Journal of Processing Engineering.

11.0 CONCLUSION

In this paper, an overview of the process parameters, material removal rate, types of generators, dielectric fluids and the minimum machinable size of the diameter are being discussed. This review is done based on previous and recent research on Micro-EDM. The paper focuses on the principal of micro-EDM, the types of EDM processes, dielectric fluid, and types of generators, EDM process parameters, and the material removal rate (MRR) and the tool wear ratio (TWR). This paper is essential for the development in the research to fabricate the micro-EDM with micro actuator tool feed mechanism machine.

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