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Present and Future Research Trend in Electro Discharge Machining

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Abstract

Electro discharge machining (EDM) is a non-conventional process used in industry for machining various intricate shapes. This process is known for machining hard and brittle conductive metallic materials as it can melt any electrically conductive material regardless of hardness at about 8000-12000 °C. History shows that, in 1770, an English scientist Joseph Priestley discovered that electrical discharge could erode metal. Then another 173 years later in 1943, two scientists Lazarenko and Lazarenko discovered that submerging electrodes in dielectric fluid made it possible to control erosion from electrical discharge. This discovery resulted in the development of the world's first EDM machines as a non-traditional machining process. Since then this EDM has been used for so many diversified applications. As such, recently there arises a question that whether this process is still non-traditional or with the successful applications of decades, it is to be called as a traditional process. With the progress of time, more and more manufacturers began to see the benefits of EDM and make it possible to manufacture delicate, intricate, and complex parts on conductive, semiconductive, and even nonconductive materials for electronic, medical, and aerospace manufacturing. This development of EDM is basically driven by dual influence namely market pull and science push. This paper presents a brief review on the EDM history and a comprehensive review on the modern applications of EDM.

Keywords: EDM, WEDM, Micro-EDM, Vibration assisted EDM, Dry EDM.

1. Introduction

Electro discharge machining (EDM) is a non-conventional and non-contact machining process used in industry for machining various intricate shapes [1-4]. This process, shown in Fig. 1 is also known for machining hard and brittle conductive metallic materials as it can melt any electrically conductive material regardless of hardness at about 8000-12000 °C [2-3, 5]. The workpiece machined by EDM depends on thermal conductivity, electrical resistivity, and melting points of the materials. The tool and the workpiece both are adequately immersed in a dielectric medium such as kerosene, deionized water, etc [3, 6-8].

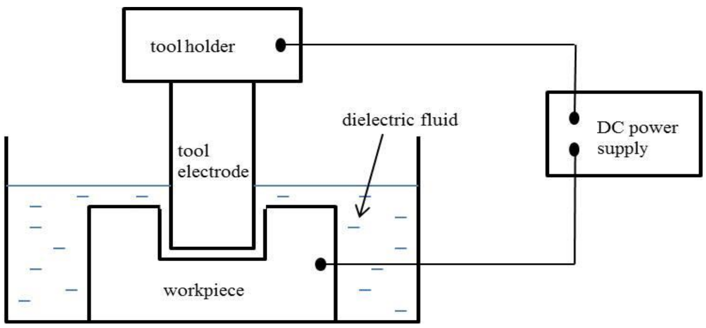

Fig. 1: Schematic diagram for EDM die-sinking [6]

Historically, this machining operation was discovered through the metal erosion by electrical sparks phenomenon reported by Benjamin Franklin in 1700 and followed by Joseph Priestley in 1770 who discovered the erosive effect of electrical discharges. In 1940's, two Russian scientist, B. R. Lazarenko and N. I. Lazarenko are the first researchers who applied the process on a machine to remove material by controlled erosion through a series of sparks. The couple invented a simple servo controller to make the EDM process more cost-effective by maintaining the gap between two conductors in dielectric liquid that helps in reducing the arcing. The developed controller was the relaxation or RC circuit where it used to be called as the Lazarenko's circuit. This type of controller is still being used until today in some of the EDM machines in order to obtain near-mirror finish structures. The first EDM machine was manufactured by the "Charmilles" in 1952 for commercial use, where later was presented in the European Machine Tool Exhibition in 1955. "Agie" and "Seibu" are among the first companies that developed the wire EDM machine in 1969 and 1972 respectively. Kurafuji and Masuzawa are the first researchers who applied EDM in micro scale by drilling a hole in a 50 µm thick carbide plate [9-10].

This discovery resulted in the development of the world's first EDM machines as a non-traditional machining process. Since then this EDM has been used for so many diversified applications. As such, recently there arises a question that whether this process is still non-traditional or with the successful applications of decades, it is to be called as a traditional process. With the progress of time, more and more manufacturers began to see the benefits of EDM and make it possible to manufacture delicate, intricate, and complex parts on conductive, semiconductive, and even nonconductive materials for electronic, medical, aerospace, and automotive manufacturing [1-4]. This development of EDM is basically driven by dual influence namely market pull and science push. This paper presents a brief review on the EDM history and a comprehensive review on the modern applications of EDM.

2. Modern Applications of EDM

This section discusses some of the present-day application of the EDM process which can be utilized in improving the quality of a product.

Micro-EDM

Micro-EDM is particularly developed to manufacture component of sized between 1 and 999 µm. In order to produce high precision and high accuracy micro geometries products with good surface qualities (roughness around 0.1 µm), micro-EDM is a suitable type of machining since the machining is done using high frequencies (>200 Hz) with small energies (10^{-6} to 10^{-7} J) and duration of 10 to 100 ns for every discharge (40 to 100 V) [11-15]. A few micron features with high-aspect-ratio (>20), burr-free, and submicron tolerances can be achieved through this technique [15].

The sparking phenomenon in micro-EDM can be divided into three phases which are ignition phase, discharge phase, and interval phase between discharges. An electrical field is created when gap voltage is applied. It is a time where highest strength is gain once the electrode and the workpiece surface are closed enough. The electrical field is capable in breaking down the insulating properties of the dielectric fluid. When the resistivity of the fluid is at lowest, a single spark is able to flow through the ionized flux tube and strike the workpiece. The spark evaporates anything in contact, including the dielectric fluid when the voltage drops as the current is produced. During this period, the spark is covered with gasses composed of hydrogen, carbon, and various oxides. When the area is struck by the spark, the workpiece surface will be evaporated and melted, resulting in a single crater. Due to the heat of spark and contaminates produces from the workpiece, the alignment of the ionized particles in the dielectric fluid is interrupted, and therefore, the resistivity rapidly increases. Voltage increases once the resistivity rises and the current drops, as dielectric can no longer endure a stable spark. At this point, the current must be switched off, which is done by pulse interval. During the pulse off time, as heat source is eliminated, the vapor that covers around the spark collapses. Its collapse creates a void of vacuum and allows the fresh dielectric fluid to flush away debris as well as cools the area. Finally, re-ionization with favorable condition happens for the following spark [14-15].

Differences between the conventional EDM and micro-EDM. Micro-EDM follows the similar principle of conventional EDM technology. However, there are some differences between these two machining. First differences would be in terms of circuitry. There are two types of pulse generators for circuit controller which are resistance capacitance (RC) or relaxation-type pulse circuitry which can be expressed through equation 1 and transistor (FET) switching circuitry. These two types of circuitry are usually used in conventional EDM. But, in order to fabricate features with several micrometers that have better accuracy and good surface roughness, than RC circuitry would be the best option since the pulse energy supplied into the gap between the electrode and the workpiece is minimum [6, 14-15].

$$E = \frac{1}{2}\left(C + C_p\right)V^2 \tag{1}$$

where, E = discharge energy, C = capacitance of the circuit, C_p = lumped parasitic capacitance present in parallel to C, and V = machining voltage [15].

EDM uses resistance capacitance relaxation (RC-relaxation) circuit while micro-EDM uses RC-pulse circuit. In RC-relaxation circuit, current and voltage are usually assumed as constant in modelling process. However, in reality, for RC-relaxation circuit, the current and the voltage are controlled at a predefined level throughout the pulse on-time. In contrast, based on the modelling process and parametric analysis, RC-pulse generator for a single discharge shows that the current and the voltage are not maintained to any predefined level. Still, the RC-pulse generator depends on the capacitor charge state at any instant. The RC-pulse circuit type is known to have low material removal rate (MRR) since it can produce very small amount of discharge energy by minimizing the capacitance in the circuit [11-15]. The second differences are in terms of dimension of plasma channel radius which rises during the spark. In conventional EDM, the plasma channel is smaller than the electrode while for the micro-EDM the size is equivalent. The third differences would be in terms of accuracy and precision. In micro-EDM, precision and accuracy of the final product are much higher since the crater size is much smaller in micro-EDM compared to the conventional EDM. Higher precision can be achieved if the electrode vibrations and wear are controlled in conventional EDM [14].

Wire EDM

Wire EDM and micro wire EDM are special types of EDM since they have the ability to cut intricate shapes and extremely tapered geometries with high performance especially in precision, efficiency, and stability [2-3]. The material removal mechanism for wire EDM and micro wire EDM operation are similar to EDM process. However, the differences are at the electrode usage where wire EDM and micro wire EDM uses winding wire as electrode while EDM uses electrode rods as the electrode [3-4, 16]. Micro wire EDM operation uses a very small diameter wire (Ø 20-50 µm) as the electrode to cut a narrow width of cut in the workpiece. The wire is pulled through the workpiece from a supply spool onto a take-up mechanism. Discharge occurs between the wire electrode and the workpiece in the presence of dielectric fluid. Discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, voltage, type of dielectric fluid, dielectric flow rate, and dielectric flushing condition are some of the important parameters that need to take into considerations during the machining operation [4, 6, 17-18]. In micro wire EDM, low electrical energy is preferable in order to avoid any ripples, cracks, and recast layer on the machined surface. In addition, short circuit may occur if there is unwanted debris at the machined area which can lead to poor surface finish [8, 19-20].

During the wire EDM operation, the most undesirable machining characteristics would be the wire breakage which affects the accuracy and the quality of the machined structures. The concentration of the electrical discharges at a certain point of the wire which leads to the increment of the temperature is one of the causes that break the wire. In addition, wire breakage may also happen due to the increase of the short circuit pulses, sudden increase in spark frequency, excessive thermal load that creates unnecessary heat on the wire, and mechanical strength of the wire. Other than wire breakage, wire lag and wire vibration also have significant effect on the accuracy and the precision of machined features. It is due to the various forces acts on the wire during the machining operation. The forces are mechanical forces from the pressure of the gas bubbles during the erosion mechanism, axial forces because of the flushing system, the electro-static forces that act on the wire, and the electro-dynamic forces from the spark generation. Several researchers suggested that the wire and the wire guide should be completely submerged with the dielectric fluid in order to reduce the wire vibration [21].

Vibration assisted EDM

Vibration assisted EDM was introduced since it has the ability in improving the machining efficiency and the accuracy of the machined parts. Ultrasonic vibration, piezoelectric actuator, and pulsating magnetic field are some of the vibration assistance that is applied in EDM [22-23]. By adding the high-frequency vibration during the EDM process, the dielectric circulation and the removal of debris tend to accelerate which leads to improving the discharge condition and the effectiveness of the discharge ratio. Most of the researchers prefer applying the ultrasonic vibration in the EDM process even though the effect mechanism is still not clear [23]. The ultrasonic vibration is usually applied at the electrode of the EDM. In wire EDM, it was found that high frequency vibration of the wire improves the sparks concentration and reduces the chances of wire breakage. According to a research, the cutting efficiency of the wire EDM increases by 30 % when ultrasonic vibration was added during the machining operation [1]. Some studies showed micro-EDM of nonconductive material is achievable when applying the ultrasonic vibration assistance during the machining process. Besides that, the machining improves when an active workpiece clamping unit with low-frequency vibration up to f = 1000 Hz at an amplitude of 20 µm peak to peak was added. The end result showed that micro-EDM process with direct vibration gives higher aspect ratio structures with improved process speed. The direct ultrasonic vibration enabled the machining of complex structures with very high aspect ratios [24]. In dry EDM, high MRR can be attained in when the ultrasonic vibration is added with the workpiece. The ultrasonic vibration has the ability to flush away the molten metal from the craters [6, 24]. It was found that the efficiency of the ultrasonic micro-EDM is eight times greater than micro-EDM when it machined the stainless steel with 0.5 mm thickness. When the vibration is applied on the workpiece, it shows that the effect of the flushing improves. The MRR also increases when high amplitude and high frequency is applied on the workpiece. To produce deep and small holes, ultrasonic vibration EDM would be the best options. 17 and 25 kHz are the normal range used as the ultrasonic frequency during experimentation [1].

EDM of semiconductive and nonconductive materials

EDM process has progressed as one of the favorable alternatives for the machining of the semiconductive and nonconductive materials [21, 25]. Researchers are applying this machining method especially on silicon and advanced ceramic materials because they are difficult to machine using the conventional cutting techniques [26]. Hence, in order to make the machining possible, assisting electrode method (AEM) is introduced [7, 25, 27-29]. AEM is a method where a conductive layer (metal plates or foils or metallic coating) is applied on top of the workpiece in order to produce sparks between the workpiece and the electrode [7-8, 25, 27, 30]. The conductive layer will be eroded during the erosion process. Polymer chains of dielectric fluid are degenerated and carbon elements are form from the cracked polymer chains due to the high temperature that occurs around the fluid during machining. The carbon elements and the conductive debris will cover the workpiece surface in order to sustain the conductivity during the machining operation. Fig. 2 shows the discharge erosion process for nonconductive materials. The commonly used dielectric fluids are the mineral oil based liquid or hydrocarbon oils since they are able to produce carbon element continuously which helps in sustaining the machining operation after the conductive layer degenerated [7, 31].

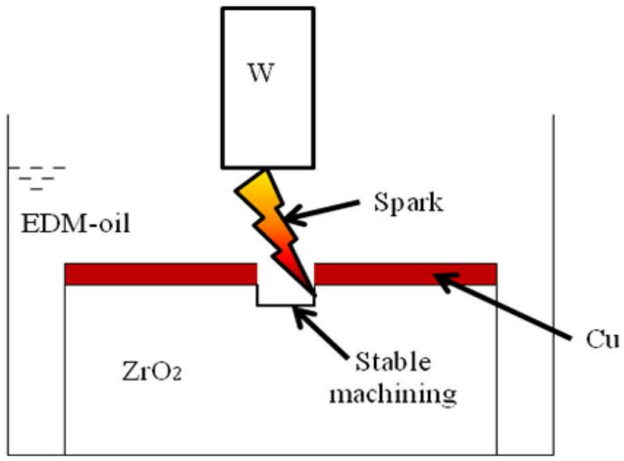

Fig. 2: Principle of discharge erosion process in EDM for ceramic [30]

The polarity of the electrode and the workpiece plays a vital role during the EDM process of semiconductive and nonconductive material. Previous researches show that higher MRR is obtainable when higher power is provided and the polarity of the electrode is negative [25, 30, 32]. This is because when the electrode is at negative polarity, more carbon elements are generated and form a conductive layer that covers the machined surface during the EDM process [30, 32]. Aside from the polarity, MRR is also depended on the rotational speed and addition of suitable chemical additives in dielectric fluid. MRR increases when high rotational speed is used since the speed improves the flow velocity of the dielectric fluid at the discharge gap as well as led the conductive layer closer to the workpiece surface. Due to these circumstances, the stability of the process and discharge energy on the workpiece surface improves [33-34]. Besides that, the rotating electrode improves the sparking efficiency for a better MRR and tool wear [35]. But, when the speed is too high, it will generate the centrifugal force that can cause the debris to escape from the machining surface [36].

It is also suggested that higher thickness of conductive layer gives better MRR [37]. However, in other research, it was found that the influence of conductive layer thickness is not as effective as the thermal conductivity of the conductive layer. The possible explanation would be that higher thermal conductivity of the conductive layer creates a substantial amount of heat at the machining gap which allows more MRR through melting, vaporization, and spalling mechanism [7, 30]. The selection of dielectric fluid also affects the MRR and the tool wear. The factors that should be considered in selecting the fluid are its properties, breakdown resistance, conductivity, viscosity, flash point, and safety [35]. Based on a study on micro-EDM of insulating silicon nitride, it shows that electrode material also can affect the MRR based on its melting and evaporation point as well as its thermal conductivity [26].

Dry EDM

Dielectric fluid is important in any type of EDM since it helps to enhance the efficiency of the machining process, improves quality of the machined surface, and flushes away the debris from the machining gap. Usually, the common dielectric fluids used are the mineral oil-based liquid or hydrocarbon oils. But, these types of dielectric fluids are harmful to the environment as well as to the machining operators. It has the capacity in generating dielectric wastes and fumes such as carbon monoxide (CO) and methane (CH_4) during the machining process which is toxic and non-recyclable. It happens when there is a high temperature during machining which may lead to the chemical breakdown of mineral oils [6, 16, 36, 38]. Hence, researchers introduce the dry EDM in order to avoid these problems [2-3, 6, 16, 39].

Dry EDM (Fig. 3) is a green machining method where gas is supplied through the pipe electrode instead of liquid as a dielectric fluid. The gas supplied aids in producing sparks between the workpiece and the electrode, eliminates the debris from the machining, and cools the machined surface [40-41]. This machining technique is also applicable for micro fabrication applications in micro level machining process such as dry wire EDM, micro dry EDM, and micro dry wire EDM [2-3, 16, 39].

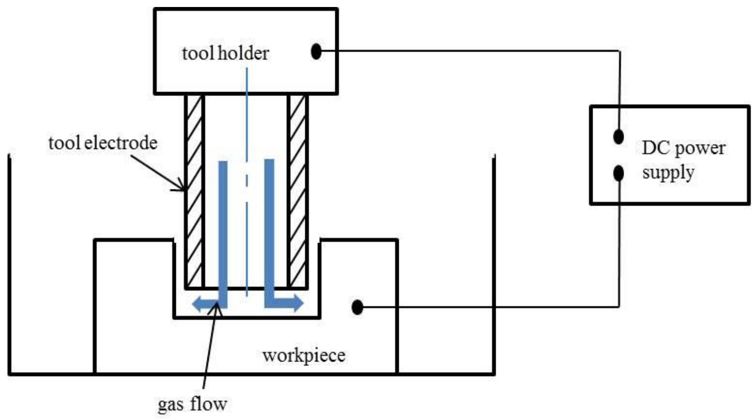

Fig. 3: Schematic diagram for dry EDM [6]

The idea of using the gas instead of liquid as the dielectric fluid is not fully agreed by certain researchers. It is because the erosion effect would be small when the sparks happened in the air since electrical discharges loses its energy. Besides that, one of the main functions of the dielectric fluid is the restriction of the spark in order to have a higher density of energy with higher performance. Hence, it is only applicable when the dielectric fluid is in liquid form. It can be explained when the dynamic plasma pressure rises and the bubble of vapour expands when the sparks is in the liquid dielectric fluid. However, since the plasma growth is restricted by the surrounding of the liquid dielectric fluid, the bubble collapses and removes the molten metal out of the crater when the temperature decreases during the off time. Although there are some disagreements among the researchers, the dry EDM was first introduced by NASA in 1985 [6, 42]. Atmospheric air, compressed air, liquid nitrogen, oxygen, argon, and helium gas are some of the commonly used gases as the dielectric fluid [6, 41, 43].

According to some researchers MRR improves when oxygen is used as the dielectric fluid [44-45]. It is because the oxidation reaction occurs with the supply of the oxygen gas increases the work removal volume during one discharge cycle. During the oxidation process, the volume of the discharge crater is enlarged. In addition, there is no corrosion on the machining surface but it may suffer from rusting due to the oxidation [1, 45]. Lower electrode wear, better surface quality, lower residual stresses, thinner white layer, and higher precision in machining are the prime outcome of this dry technique [1, 16, 43]. When the polarity of the electrode is negative, the electrode wear is smaller and the MRR is higher compared to the positive polarity [1, 43]. Low electrode wear ratio in dry EDM is due to the small physical damage of the electrode caused by the reactive force. It is because the dry EDM is free from the vaporization of liquid dielectric fluid when the discharge occurs. Besides that, adhesion of machining debris on the electrode helps to reduce electrode wear [45]. Some researchers suggested that dry wire EDM and micro dry wire EDM can be used for finish cut especially in manufacturing high precision dies and molds [1].

3. Conclusions and Future Direction

Even though EDM is known as a traditional machining process, it has successfully come up with the applications that can fulfill the requirements in producing complex three-dimensional features. Fundamentally, the basic principle of the EDM process is almost the same for all of its applications. But, certain modification is necessary depending on the requirements of the application. It is known that the origin of EDM starts from the industry. However, in the present day, EDM is most likely popular between the researchers because in order to improve the performance of the process, continuous research or investigation is needed. This improvements lead to the applications of the EDM. This application of EDM is basically driven by dual influence namely market pull and science push. Hence, as for the future direction, EDM applications starts to attract manufacturers in fabricating delicate, intricate, and complex parts on conductive, semiconductive, and even nonconductive materials for electronic, medical, and aerospace manufacturing industry.

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