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A State-of-the-art Review on Micro Electro-Discharge Machining

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Abstract

Electro-Discharge Machining (EDM) is one of the non-conventional machining processes available, in which the material removal takes place due to melting and vaporisation of electrode materials. Micro Electro-Discharge Machining (μ-EDM) is a variant of EDM, is playing an important role in generation of micro features on difficult to machine conducting materials. In this paper, authors carried out an extensive literature study to give a complete description on μ-EDM process, its requirements, performance and applications. More than fifty papers were referred and the details were categorized into five major areas, namely, experimental setups and its subsystems, experimental studies and optimization methods, generated micro features, modeling and simulation approaches and applications.

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Keywords: μ-EDM ; dielectric fluid; micro features; modeling, optimization, tool feed mechanism

1. Introduction

EDM also referred to as spark machining is a manufacturing process whereby a required shape of an object is obtained as a mirror image of the tool. The material removal from the workpiece occurs by a series of rapidly recurring spark discharges between the two electrodes, which, results in extremely high temperature usually in the order of 8,000 ^{0}C to 12,000 ^{0}C causing vaporisation of the material at the point of discharge. The vapourized material is dispersed into the space surrounding the electrodes. Melting and vaporization of the material leads to the

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formation of tiny craters on the work surface. EDM has proved to be an effective method to machine metals irrespective of their hardness and other mechanical properties. But thermal properties such as melting point, boiling point, heat conduction efficiency and heat capacitance influences the process only to a very small extent, as the temperature generated by the electrical discharges exceeds the boiling point of any material on earth [1]. μ-EDM has capability to machine microstructures of varying complexity levels on difficult to cut metals and alloys. According to College International pour la Recherche en Productique (CIRP) Scientific Technical Committee Paper, the term micro-machining defines the processes that machine dimensions in the range of 1 μm to 999 μm [2]. μ- EDM has gained importance because of its ability to produce stress free micro sized cavities of desires shapes on conducting and semi conducting materials. Even though the principles of conventional EDM and μ-EDM are the same, there are some differences between the two processes, which arise due to the scaling effect. Table 1 shows the major differences between the conventional EDM and μ-EDM.

Table 1. Major differences between the conventional EDM and μ-EDM.

Parameters	Conventional EDM	μ-EDM
Size of the tool	Greater than 999 μm	Lesser than 999 μm
Inter electrode gap	10 to 500 μm	Less than 10 μm
Open circuit voltage	4 - 400 V	10 - 120 V
Peak current	Greater than 3 A	Lesser than 3 A
Pulse on-time	0.5 to 8 ms	50 ns to 100 μs
Specific energy	High	Low

μ-EDM process can be divided into four categories based on the type of tool and tool kinematics. They are μ-wire EDM, μ- die sinking EDM, μ- milling EDM and μ-EDM drilling [3]. In this, paper a complete review of ongoing/completed research in the field of μ-EDM and its possibilities are presented.

1.1. Principle of μ-EDM

The working principle of conventional EDM, various components, subsystems, applications etc are detailed in text books [4, 5]. In μ-EDM, the two electrodes-workpiece (anode) and tool (cathode) separated by dielectric fluid are supplied with pulsed voltage. Figure 1 shows the schematic representation of μ-EDM cell.

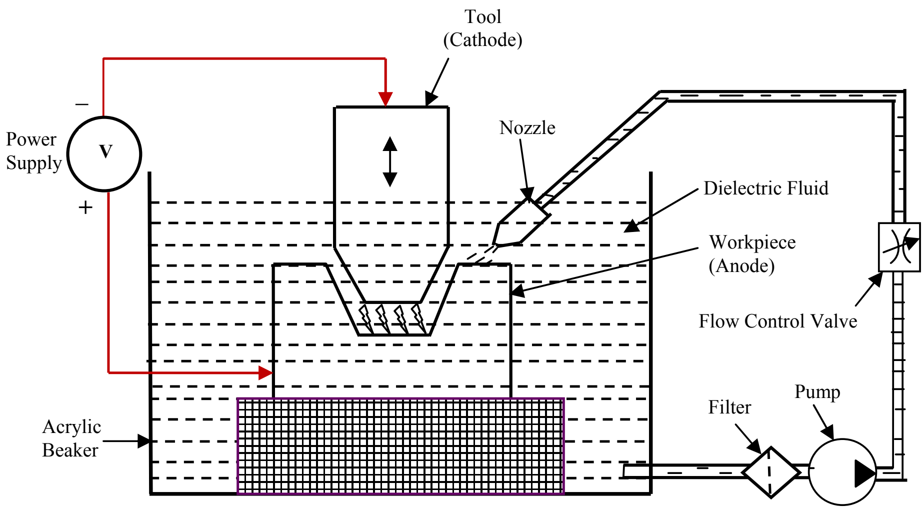

Fig. 1. Schematic representation of EDM cell.

The workpiece and tool are brought closer until the dielectric in the media breaks down and allow current to pass through it which appears as sparks. By varying the electrical process parameters such as voltage, frequency, current, duty cycle etc., it is possible to control the energy of sparks**.** Application of pulsed voltage at discharge energies in the range of few micro joules that result in continuous material removal in μ-EDM. μ-EDM provides immense possibilities to produce tiny features, micro components and even fabrication of Micro Electro Mechanical System (MEMS) devices.

2. Review on μ-EDM process

This section focuses on the reviewed literatures of research areas and the current trends in μ-EDM. Figure 2 shows the classification of research papers.

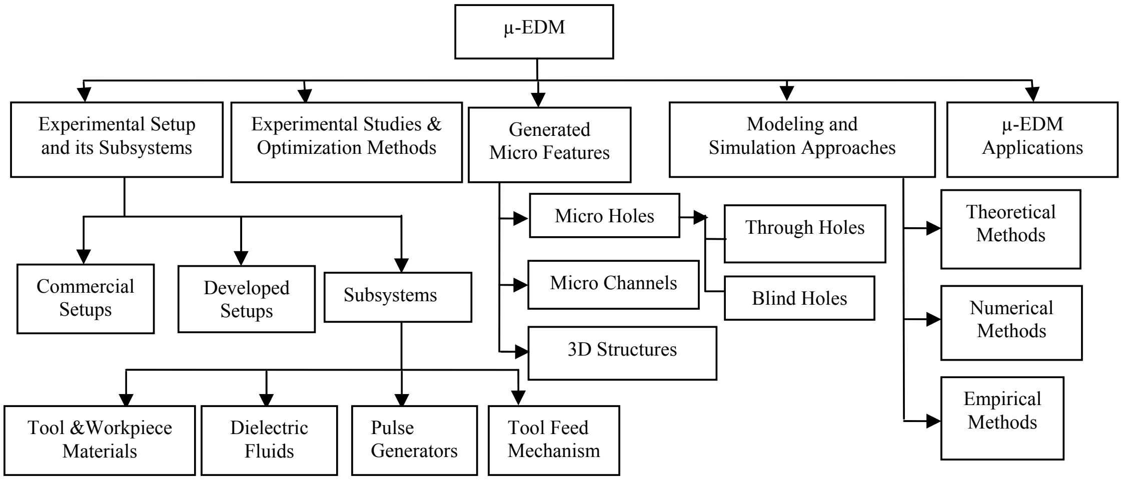

Fig. 2. Classification of research papers.

2.1. Experimental setups and its subsystems

Most of the research work carried so far on μ-EDM is on commercial available μ-EDM machines. There are only a very few manufacturers supplying μ-EDM machines. Some of the researchers utilized these commercial available machines such as SARIX [6, 7, 8, 9], Panasonic Factory Automation, Pacific Controls and SmalTec. Details of the commercial available μ-EDM systems and their capabilities were collected and summarized [10, 11].

At the same time, a large number of researchers have focused on development of μ-EDM setups that suit their requirements to conduct experiments. **Higuchi et al.** [12] developed a pocket sized EDM with a volume of one thousandth than that of the conventional ones having the performance same as a conventional EDM. **Lim et al.** [13] developed a μ-EDM, which is energized by a pulse generator that can be switched to both transistor type and RC-type. **Gang et al.**[14] developed a precision μ-EDM which consists of high precision XYZ stages with the resolution of 0.1 μm driven by linear motor, a high speed rotary spindle with rotation accuracy within 1 μm, high precision granite base, small energy power unit and video microscopic system with high enlargement factor which is used to monitor the state of machining online. Fig. 3 shows the developed μ-EDM machine. **Chow et al.** [15] modified a conventional EDM machine by fitting a rotating disk as the electrode to machine micro slits. **Leera et al.** [16] proposed an indigenously developed μ-EDM setup. The schematic diagram of the proposed μ-EDM experimental setup is shown in Fig. 4.

It consists of copper plate as workpiece electrode, copper wire as tool electrode of diameter 300 – 800 μm, peizoactuated tool feed mechanism, transistor based pulse generation circuit, deionized water as dielectric fluid, and ultasonicator containing the dielectric fluid. μ-EDM subsystems are categorised into workpiece electrodes, tool electrodes, dielectric fluids, pulse generation circuits, tool feed mechanism and its circuits.

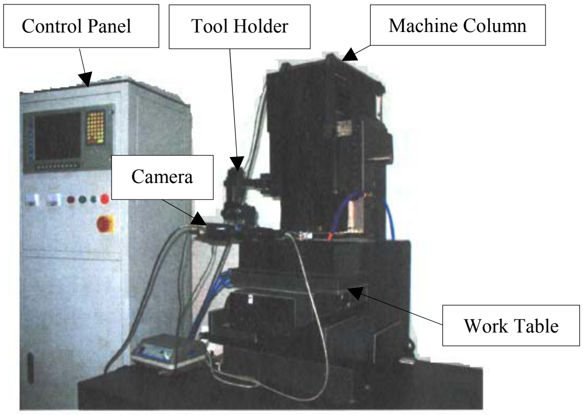

Fig. 3. Developed μ-EDM setup [12].

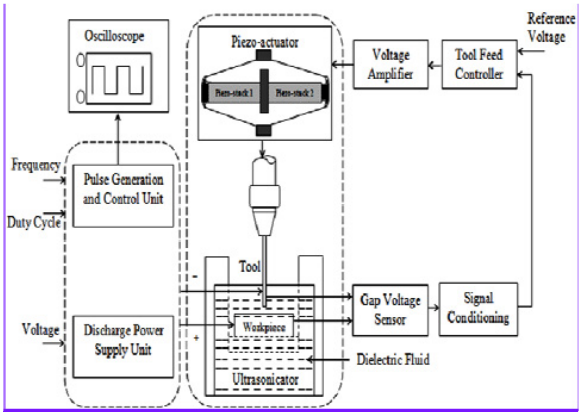

Fig. 4. Schematic diagram of the proposed μ-EDM setup.

The detailed explanations of these components are elaborated below:

1. Workpiece materials: A variety of metals and alloys can be machined using μ-EDM setup. The various materials machined using μ-EDM found in literature are copper [16, 17, 18] titanium alloy Ti-6Al-4V [19, 20], SK3 carbon tool steel [21], SS304 [22, 23], high nickel alloys [24], tungsten carbide [25, 26], ceramics [8, 10].

2. Tool materials: Selection of tool in μ-EDM is a critical factor, as the accuracy and shape of the micro feature machined largely depends on the tool. Tungsten electrodes [27, 28] and tungsten carbide electrodes [20, 21, 26] are the preferred tool materials in μ-EDM. To complement this widely used expensive material, cost effective materials namely brass [23], copper[16, 29], graphite and stainless steel are also tried as tool electrodes.

3. Dielectric fluids: The commonly used dielectric fluids are deionized water [30] and kerosene [28, 21]. Total EDM 3 oil [23], hydro carbide dielectric liquids [31] etc are the other dielectric fluids used in μ-EDM process. Researchers have added micro molybdenum di-sulphide (μ-MoS_2) powder in dielectric fluid and using ultrasonic vibration during μ-EDM processes to improve surface finish and MRR [28].

4. Pulse generators: The commonly used pulse generators in μ-EDM are RC type, transistor-type and transistor-type iso-pulse generators. In RC type of generators, the capacitor stores the energy and this energy is discharged during the machining process. Whereas in transistor type pulse generators, the capacitor is replaced by a transistor which switches the pulses to generate rectangular pulses between 0V and 60 V, supply voltage. RC type generators are preferred to transistor type because of high discharge frequency and low discharge energy [17]. In most cases, transistor-type generator has been used to supply the discharge energy which is good for conventional EDM [32]. **Jahan** [25] studied, RC-type circuit could be more suitable for fabricating microstructures in tungsten carbide, where accuracy and surface finish are of prime importance.

5. Tool feed mechanisms: For interrupted machining the gap between the tool electrode and the workpiece electrode should be maintained constant. The function of tool feed mechanism is to raise or lower the tool by sensing the voltage fluctuations in the inter electrode gap, so that a constant inter electrode gap is maintained. Servo feed control mechanism is used in most of the setups [32, 33]. Whereas some researchers used different technology based micro actuators to impart the tool movements and these have proved to be more efficient compared to the conventional servo controlled tool feed mechanisms. **Han et al.** [32] proposed a new servo control tool feed mechanism that senses the average gap voltage and uses it as the feedback signal to control the feed, so that the electrode gap is maintained constant. **Mahendran et al.** [34] developed a μ-EDM system with directly mounted APA 400MML Actuator as the tool feed mechanism. **Li et al.** [35] have proposed an inchworm type micro feeding mechanism. Impact drive mechanism [12] and direct drive method [34] based on piezoelectric actuation were also proposed and elaborated. **Leera et al.** [16] developed a μ-EDM system with a piezoactuated tool feed mechanism to maintain a constant gap between the electrodes.

2.2 Experimental studies and optimization techniques

μ-EDM is a thermal process, where in electrical power supplied creates the thermal effect to remove material. Therefore, the input electrical power is a matter of significance. The electrical input conditions generally consist of several parameters such as current, voltage, frequency, pulse on-time, pulse off-time, duty cycle etc. Most of the papers have focused on tuning these process parameters to achieve optimum performance measures like MRR and TWR. The process parameters are classified as electric and non-electric parameters to study their effects on machining. The electrical parameters are voltage, frequency, pulse on-time, pulse off-time, discharge energy, duty cycle etc. The non-electrical parameters are dielectric fluid, flushing pressure, frequency of induced vibrations addition of some particles of micro and nano size to enhance the machining rate etc. Two performance measures that greatly judges efficiency of μ-EDM process are Material Removal Rate (MRR) and Tool Wear Rate (TWR). Surface roughness, dimensional accuracy, taper, overcut (OC) etc are the performance measures of quality of the machined feature mainly holes and channels. The parameters are analysed and optimized using various diagnostic studies like grey relational analysis, Taguchi method, multi objective optimization, ANOVA, Genetic Algorithm (GA) etc. The available literatures on this area are as follows. **Tiwary et al.** [19] carried out a study on the influence of various process parameters on MRR, TWR, OC, and taper angle while machining of Ti–6Al–4V. To perform the experimentation, they have utilized Central Composite Design (CCD) to design the experiments and Response Surface Methodology (RSM) to map the relationship between the input process parameters with the resulting process response. **Lin et al.** [21] also used RSM based on the CCD for evaluation of the characteristics Electrode Wear Rate (EWR), MRR and OC. **Natarajan et al.** [36] carried out optimization of multiple performance characteristics - MRR, TWR and OC, using Taguchi method and Grey relational analysis. The parameters selected by them were pulse on-time, discharge current and gap voltage. **Meena et al.** [20] carried out multi objective optimization of μ-EDM machining parameters of Ti-6Al-4V alloy by the grey relational analysis and analysis of variance (ANOVA). **Mehfuz et al.** [37] investigated the influence of process parameters, feed rate, capacitance, and voltage. The response variables were average surface roughness (Ra), maximum peak-to-valley roughness height (Ry), TWR and MRR. **Pandey et al.** [22] carried out studies on optimization of the process parameters using RSM and GA. **Leera et al.** [17] studied the interaction effects of process parameters on width, OC and surface roughness of micro channels machined on μ-EDM using Taguchi method and RSM.

2.3 Generated micro features

The micro features of interest in machining using μ-EDM are micro holes- blind and through holes, micro channels, micro grooves, micro slits, three dimensional structures and textured surfaces. These promising features that can be machined with a high level of accuracy using μ-EDM have a great demand in industry. This section discusses the literature corresponding to machining of such micro features.

Micro holes are common features of many micro products – catheters, injection needles, nozzles, cooling holes on turbine blades, dies etc. μ-EDM is very effective to machine any kind of holes such as small diameter holes down to 10 μm and blind holes with an aspect ratio of 20. **Maity et al.** [28] observed that circularity error, recast layer formation and longer machining time during micro hole machining was mainly due to the effect of capacitance value used. **Jahan et al.** [26] conducted experimental investigations on μ-EDM for obtaining high-quality micro-holes in WC with small spark gap, better dimensional accuracy, good surface finish and circularity. **Rajurkar et al.** [38] reported that μ-EDM can be easily used to produce a hole of depth equivalent to five times the bore diameter. **Yeo et al.** [39] investigated feasibility of a magnetic field to obtain higher aspect holes on hardened tool steel using μ-EDM process. **Natarajan et al.** [23] carried out a study on machinability and accuracy of microholes machined on grade 304 stainless steel using μ-EDM. **Tahsin et al.** [31] studied the shape and dimensional geometry of blind micro holes machined on plastic mold steel using μ-EDM. **Ekmekci et al.** [40] experimentally investigated the geometry and subsurface damage of blind micro-holes produced by μ-EDM on plastic mold steel to explore the relational dependence with respect to pulse energy. **Liu et al.** [24] investigated the feasibility of machining high nickel alloy using µ-EDM, and they were successful in doing it. Micro channel is one of the most necessary feature in many micro devices and systems and have found research interest in a wide range of sectors including biomedical, energy, chemical, micro fluidics, micro molding etc. **Murali et al.** [41] demonstrated the fabrication of micro channels of width 25 µm and surface roughness with R_a value 0.4 µm on titanium alloys. **Modica et al.** [6] conducted a study on process optimization during machining of micro channels. **Hung et al.** [42, 43] used µ-EDM method to produce micro channels with aspect ratio 1.2 on metallic bipolar plates. **Oscar et al.** [44] proposed a new system to machine micro channels using an oscillating electrode by designing an electrode holder capable of getting required oscillation. **Schubert et al.** [45] successfully demonstrated µ-EDM milling of non-conductive ZrO_2 ceramics by creating an electrically conducting starting layer. **Ali** [27] compared micro end milling and micro electrical discharge milling for the fabrication of micro channels on metals. **Tong et al.** [46] machined non-circular cross section microstructure using a vibration assisted EDM process. A novel multiprocessing µ-EDM technique was used to fabricate complex 3D structures like micro lollipop end mills [47].

2.4 Modeling and simulation approaches

The various process parameters affecting the µ-EDM process as mentioned in section 2.2 are voltage, current, capacitance, feed rate etc. Researchers have tried various modelling and simulation approaches to study the effect of various parameters on MRR, TWR, surface finish etc. The models are broadly classified as analytical models for mathematical analysis, numerical models using Finite Element Method (FEM) as tool and empirical models from experimental studies to relate the effect of parameters on various responses. **Murali et al.** [48] developed a mathematical model based on heat transfer principle for the simulation of single spark machining during µ-EDM of titanium alloy. **Dhanik et al.** [49] developed a comprehensive model to predict the material removal in a single discharge in µ-EDM using the basics of EDM models. **Sarikavak et al.** [50] developed a 3 D transient model for single discharge to calculate the MRR and radius of the crater formed. **Wang et al.** [51] suggested a thermo-physical model for µ-EDM deposition process. FEM was used for the numerical analysis of single spark deposition. **Tan et al.** [52] conducted a new heat conduction analysis of µ-EDM with FEM. They have also proposed a new approach for predicting the effects of multiple discharges on machining performance. **Tan et al.** [53] proposed a numerical model based on the multiple discharge approach to predict the thicknesses of the recast layer produced using the µ-EDM process. **Somashekhar et al.** [54] developed a numerical model based on Finite Volume Method (FVM) to solve the micro-EDM model equations so that the effect of spark ratio on the temperature distribution in the material can be predicted. **Pradhan et al.** [55] developed an Artificial Neural Network (ANN) model using a back-propagation neural network algorithm, which was trained with response values obtained from the experimental results. Empirical models for optimization based on RSM were developed to predict the response parameters for any arbitrarily input parameters.

2.5 Application areas

µ-EDM finds wide applications in inkjet nozzles of printers, cooling holes in turbine blades, micro channels in micro fluidic analysis, micro moulds, honeycomb structures etc. Some of the research works from literature are as follows: **Allen et al.** [56] used µ-EDM process to machine inkjet nozzles. **Tong et al.** [57] used µ-EDM process to drill high quality drilling spray holes on diesel injector nozzles. **Oliaei et al.** [47] fabricated tungsten carbide and Poly Crystalline Diamond (PCD) ball end mills using µ-EDM process. **Sahu et al.**[58] generated nano particles of mean diameter less than 10 nm using µ-EDM finds its application as an efficient coolant in automobile sector. A novel experimental approach-Ultrasonic technique for concentration characterization of copper nanofluids is elaborated [59]. **Liu et al.** [60] demonstrated the applications of two and three-dimensional microstructures on different types of materials such as a stainless steel micro-compressor and a ceramic miniature gas turbine.

3. Conclusions

µ-EDM is one of the important non-conventional machining methods that can find wide application. In this connection, authors reviewed many papers on µ-EDM and concluded that there are large research potentials in this area. The outcome of this review makes the reader to think in the direction of various issues as discussed in the paper as:

- Experimental setups and its subsystems
- Experimental studies and optimization techniques
- Generated micro features
- Modeling and simulation approaches
- Application areas

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