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A REVIEW PAPER ON ELECTROCHEMICAL DISCHARGE MACHINING PROCESS (ECDM): ANALYSIS OF SPARKING ACTION AND FUTURE ASPECTS

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Abstract

In the present scenario of worldwide growth in the manufacturing segment, non-traditional machining (NTM) processes are most widely used for machining of variety of materials. Amongst these NTM processes, Electrochemical discharge machining (ECDM) has been proven as a competent machining process to produce variety of multifaceted shapes efficiently on difficult to machine materials. ECDM is a non-conventional machining process that combines electrochemical machining and spark erosion to produce high-precision parts. The current article is focused on review of different areas of ECDM including its variants, key domains, sparking phenomena, etc. Furthermore, this article also covers outlook of future work in the field of ECDM. Overall, this review article aims to provide a comprehensive understanding of ECDM which can help researchers and practitioners to optimize the process and minimize its environmental impact.

Keywords: NTM; ECDM; ECM; EDM; Optimization Techniques.

1. INTRODUCTION

Manufacturing processes have been developed since the 'Stone Age'. Machining is a kind of manufacturing processes which is classified as conventional and non-conventional machining. The conventional process of machining removes material from the work piece in variety of chips with the cutting tool harder than work piece material. In non-conventional or nontraditional machining (NTM) process, removal of material takes place with or without chip formation and physical tool may or may not be present and tool material is not necessary to be harder than work piece material. These nontraditional machining processes have paved the way for new expansion in the field of nano and micro machining. These processes were industrialized and commercialized during the 1980s [1], [2]. The unique features of NTM processes such as, high productivity, high accuracy, close degree of tolerances etc. has made them more significant and popular in the today's manufacturing environment [3]. These NTM processes are widely classified according to form of energy used like thermal, chemical, electrical, electrochemical, sound, light and many more [4].

In present era, micromachining is a demanding sector because of manufacturing of variety of micro components, such as, inkjet nozzles, micro components like sensors, pumps, tools, reactors, chips, micro electro mechanical systems (MEMS) and many more. These micro components are widely adopted in the emerging industrials segments [5], [6]. These micro products are fabricated by different conductive materials [7], [8] as well as advance non-conductive engineering materials [9]. However, it is problematic and challenging task for industrialists to achieve high dimensional accuracy using conventional machining process. This is because of, hardness, brittleness and metallurgical properties of these materials. Some other problems may also be reason for complexity in machining, such as, cutting tool failure, chattering phenomenon and poor surface quality [10]–[13].

To conquer these troubles, NTM processes are the only solution and widely adopted by industrialists [14], [15]. These processes are, such as, electro chemical machining (ECM), electric discharge machining (EDM), wire electric discharge machining (WEDM), electron beam machining (EBM), laser beam machining (LBM), plasma beam machining (PBM), ultra-sonic machining (USM), abrasive water jet machining (AWJM), abrasive jet machining (AJM), and many more. Among these NTM processes, EDM and ECM processes are identified as the most comprehensively accepted and commercialized processes used for micro machining because of their ability to fabricate intricate shapes on the variety of materials [16], [17].

In EDM process mechanism, material removal takes place from a progression of sparks produced between anode and cathode deeped in a dielectric medium. Between the electrode and the work piece, this medium works as a deionizing zone making availability of optimized sparks [18], [19]. However, in ECM process mechanism, material removal takes place through electrolysis process followed by 'Faraday's laws of electrolysis' [20], [21].This phenomenon generates replica of the tool on the work piece. ECM has broad range of its applicability regardless of any limitations of hardness of the material, tool wear rate, constraints of material removal rate (MRR), surface quality, and stress free and crack free components etc. [22]. It has vast applications in different segments, such as, aerospace [23], [24], biomedical [25], [26], deburring [27] , energy [28]–[32], deep hole machining for automotive applications [33]–[35], tribology [36] and this process is more suitable for bulk production [37]. Furthermore, it is used for machining of variety of materials including conductive and hard materials, like, metals [38]–[40], semiconductors [41]–[43], composites [44]–[46] and many more. ECM process uses variety of electrolytes including, acidic, basic and neutral solutions [47].

However, EDM and ECM processes are commercially available and widely adopted number of industries, although, there is constraint of machining of only conductive nature of materials [48]. Further, EDM have certain issues related to surface integrity [49]–[52], MRR, heat affected zone (HAZ) and tool wear rate (TWR) [53]–[56]. However, ECM has good surface quality with prevention of formation of HAZ, but there also exists major issues associated such as decreased MRR and dimensional accuracy [57].

These issues encouraged the researchers to develop such a hybrid process which have combined features of individual machining process i.e. EDM & ECM into single process and resulted in ECDM process [58]–[60]. After thorough analysis, a comparative chart has been presented among EDM, ECM and ECDM processes by taking into consideration different aspects of machining as shown in Table 1.

Table 1. Comparative Chart of EDM, ECM and ECDM

Process	EDM	ECM	ECDM
Sparking mechanism	Collapse of dielectric between the electrodes	No spark phenomenon takes place	Various models proposed by researchers
Components used for machining	Electrodes and Dielectric	Electrodes and Electrolyte	Electrodes and Electrolyte
Material removal mechanism	Melting and vaporization of material of work piece	Electrochemical reaction takes place resulting in anodic dissolution	Melting and vaporization of work piece because of the heat generated by ECD phenomenon
Uses in commercial market	Yes	Yes	No
Level of eco-friendliness	High	Low	Medium
Nature of work piece material used	Conductive material	Conductive material	Conductive, non-conductive and advance engineering materials
Location of discharge	Between electrodes	No discharge action	At smaller electrode
Thermal induced imperfection	Yes	No	Yes

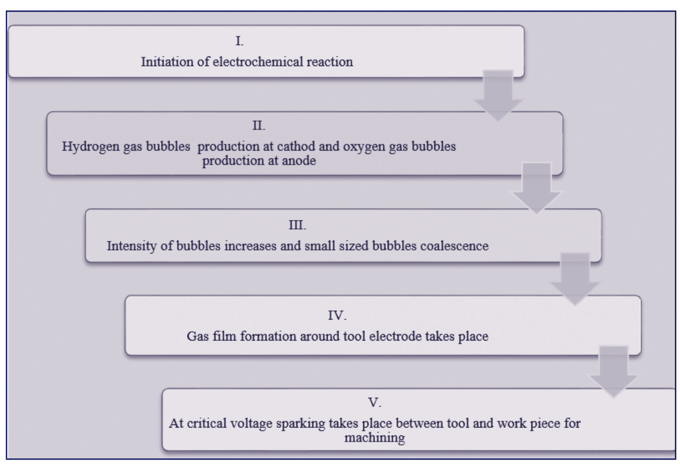
2. ECDM: A HYBRID MACHINING TECHNOLOGY

Now-a-days, industries are striving for green technology and sustainable manufacturing in order to have safer breathing zone of the operator [61]. [62], [63]. ECDM has proven to be best choice as a 'Hybrid machining process' fulfilling these criteria. Electrochemical Discharge (ECD) occurrence in ECDM has developed as a combination of Electric Discharge (ED) and Electro Chemical (EC) phenomenon and having characteristics of both processes [64].

A general experimental setup of ECDM consists of mainly two electrodes i.e. anode and cathode. Tool electrode acts as 'cathode' and auxiliary electrode acts as 'anode'. An electrolyte tank is kept underneath the cathode and the work piece is kept below the tool electrode with partial immersion in electrolyte upto a few millimeters. A few centimeters gap is kept between anode and cathode.

In order to create electrochemical cell (ECC), DC power is supplied over the two electrodes. Further, electrolysis process begins because of the potential difference across anode and cathode causing development of H_2 gas bubbles at cathode tip. If applied voltage is fewer than peak voltage, O_2 gas bubbles are produced at auxiliary electrode. With further increase in voltage, bubble growth takes place and coalescence to form a gas film acting as an insulation layer for electrolyte and tool electrode. As voltage is increased above peak value, spark produces at tool electrode. Sparking phenomenon results in melting and vaporization of material [65]. The state-of-art mechanism of ECDM process is categorized as, (a) electrolyte evaporation and bubble formation (b) bubble coalescence phenomenon (c) gas film development (d) sparking action and (e) machining due to thermal erosion. Further, the detailed flow chart of spark occurrence in ECDM is as shown in figure 1.

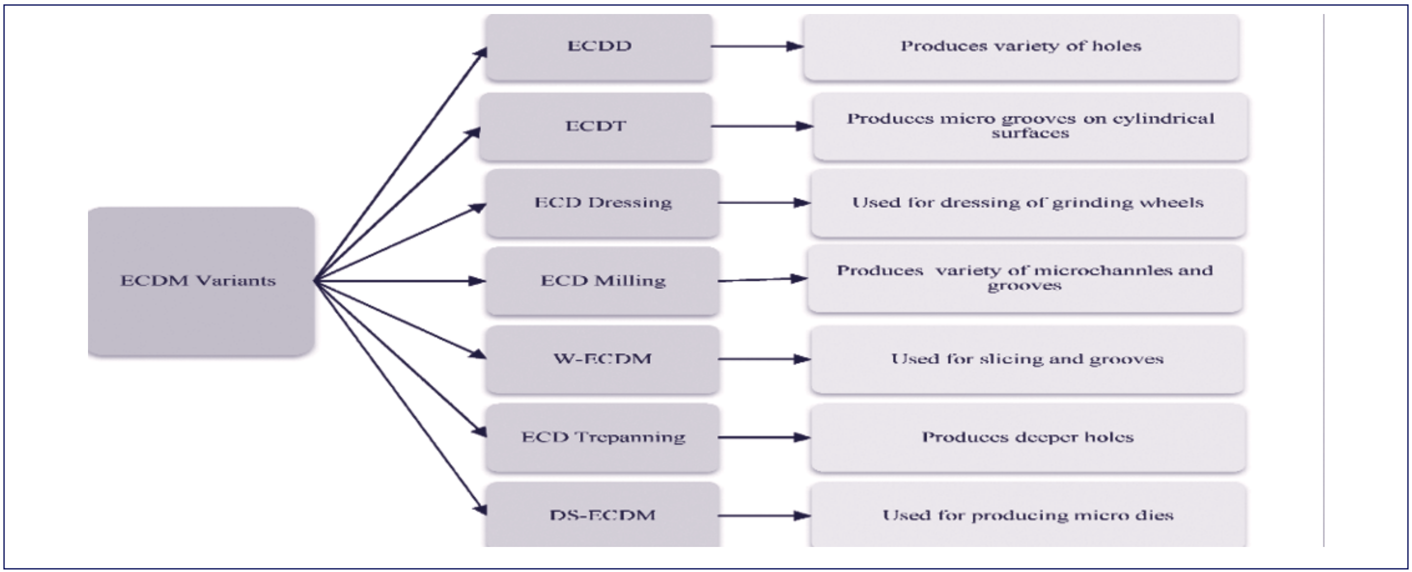
Figure 1. Flow Chart for spark occurrence in ECDM Process



2.1 ECDM Variants: ECDM can be performed in number of ways called 'variants' of ECDM and these are broadly classified as per their principle of operation using electrochemical discharges (ECD). These variants are, such as, ECD drilling, ECD milling, ECD turning, ECD dressing, wire ECDM, die-sinking ECDM, ECD trepanning. The classification chart of these variants is as shown in Figure 2.

2.1.1 Electrochemical discharge drilling: This method is widely used to produce high quality precise holes. However, variety of methods can be used for drilling operation, such as, Ultra Sonic Machining (USM) [66]–[69], diamond-wheel assisted grinding [65], [70]–[73], Abrasive Jet Machining (AJM) [74], [75], Laser Machining (LM) [76]–[79] and many more but higher machining cost, expensive equipment, low surfaces finish, high power consumption, lower MRR are certain limitations which restricts the use of these methods.

Figure 2. ECDM Process Variants [80]



There are number of factors which affect the drilled hole quality, depth, overcut and many more hole characteristics. These parameters are such as, type of electrolyte, power supply conditions, tool electrode etc. that affect sparking action during ECDD phenomenon. Initially in 1997, a study firstly focused on hole drilling of ceramics because of its increasing demand in many industrial and non-industrial applications. The study used the concept of 'Gas-filled electro discharge and electrochemical compound machining (GFEECM)' and claimed high energy saving with improved efficiency of the machining process in comparison to conventional technologies [81]. During drilling of non-conducting materials, 'Limiting depth' of hole drilling was identified as a major issue for specific range of applied voltage and electrolyte conductivity due to some constraints [82]–[89]. Focusing at this issue, a number of researchers worked for betterment to machine deeper holes with improved quality. Researchers have claimed the use of ECDD for effective machining of a number of different conductive and non-conductive materials. The non-conductive materials covered in the previous studies for ECDD are borosilicate glass [90]–[92], pyrex glass [93], [94], soda lime glass [95]–[98], glass wafers [99], other glass material [59], [82], [90], [100]–[104], silicon wafers [105], e-glass-fiber-epoxy composite [106], zirconia ceramics [66], [107], [108], silicon nitride ceramic [109], [110], alumina ceramic [66], [111]–[113], SiC reinforced polymer [114], hybrid polymer matrix composites [115], silicon carbide reinforced epoxy composites [116], silicon carbide particle matrix composites [117] and many more. The conductive materials covered in the previous studies for ECDD are metal matrix composites [114], [118], [119], steels [120]–[123], super alloys [124], [125], beryllium copper alloy [126] and stainless steel [38], [55], [127] and many more.

2.1.2 Electrochemical discharge milling: For fabrication of complex 3D microstructures, electrochemical discharge milling process has proven to be a best choice of the researchers. Glass and quartz material are widely machined by this process. In this process, for machining purpose, a rotary cylindrical wheel is used which is working as a cathode electrode. TRR and TTR are identified as the two major influencing parameters having impact on the performance of process. A number of studies have been reviewed that adopted this process for fabrication of µ-geometries [128]–[130], µ-channels surface texturing [131], and µ-grooves [132], [133] etc.

2.1.3 Electrochemical discharge turning (ECDT): ECDT is widely adopted for machining of cylindrical work piece with continuous rotation. The work piece revolution is the key parameter in ECDT that affects supply of fresh electrolyte in inner machining zone, which is responsible for evaluating machining performance. Wuthrich et al. studied for machining of narrow and deep grooves to identify optimized values of rotation rate where improved machining performance can be achieved [102].

2.1.4 Electrochemical discharge dressing: This process is used for worn grinding tool dressing which is the major requirement in most of industrial applications [134]. In this process, worn grinding tool acts as cathode and auxiliary electrode acts as anode. The worn grinding tool is dipped into electrolyte bath and ECD action helps to wear down the wreckage and metallic bonds from the worn grinding tool surface and resulting in damage free extended bits on the grinding wheel.

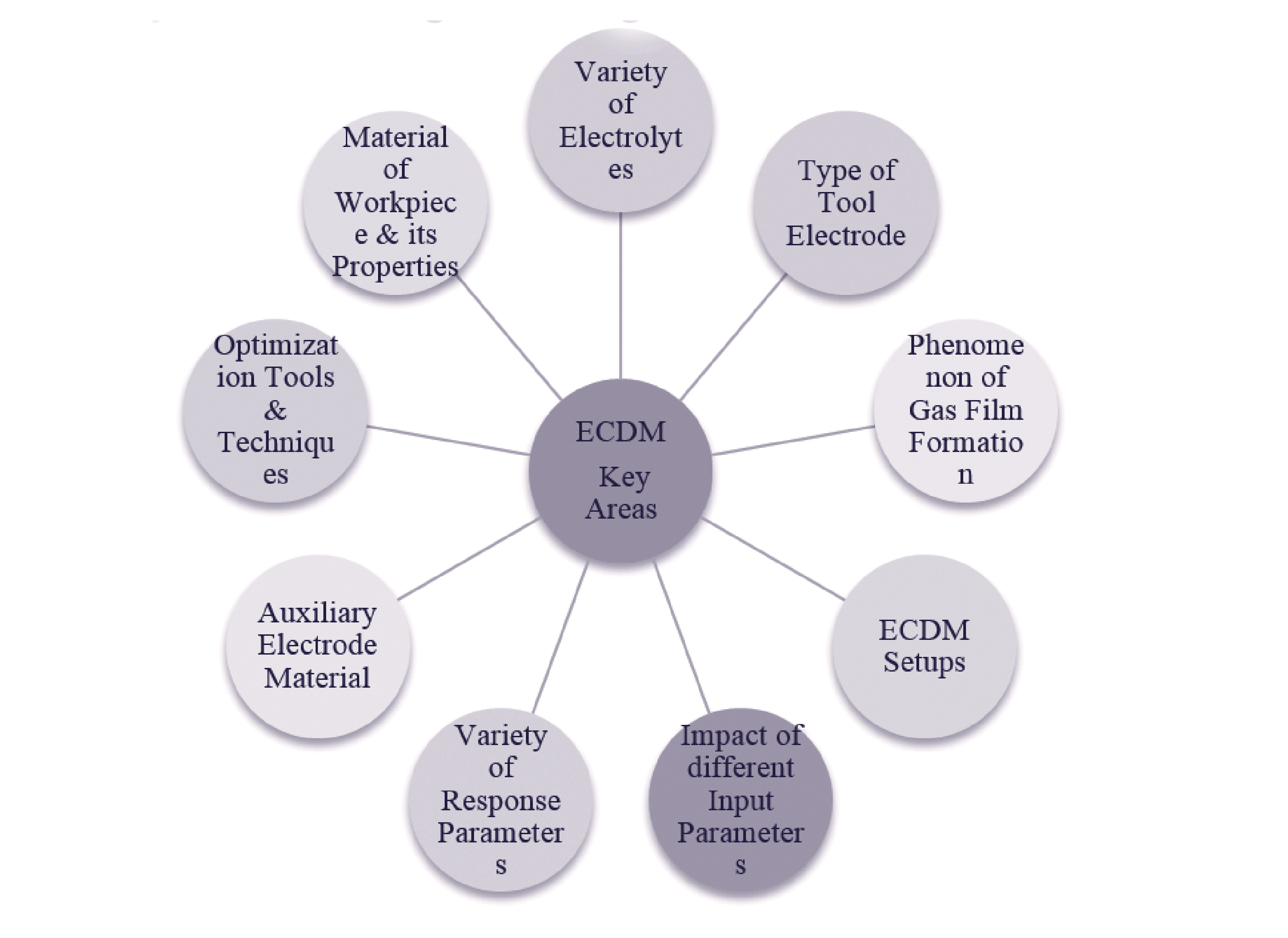
2.1.5 Wire electrochemical discharge machining (W-ECDM): W-ECDM is adopted for machining in form of slicing of hard and brittle material [111] in which travelling wire works as cutting tool (cathode) and fully dipped in the electrolyte [135]. There are numerous studies showing the use of WECDM for variety of materials, such as, quartz [110], ceramics [136]**,** composites [137] and many more.

2.1.6 Die-sinking electrochemical discharge machining DS- ECDM is used for manufacturing of small and thin dies irrespective of their thermal conductivities. Previous studies show that DS-ECDM is widely adopted for both conductive [138] and non-conductive [139] materials. Higher surface integrity is observed by DS-ECDM in comparison to ECM and EDM.

2.1.7 Electrochemical discharge trepanning: This is a kind of deep hole-drilling method, which is modified form of ECDD. In this method, an offset is provided between tool axis and spindle axis in order to have an orbital motion of tool electrode. A study reported this method as an alternative of ECDD to avoid constraint of limiting depth [140]. A study employed use of spring fed abrasive electrode by replacing gravity fed electrode with pulse DC supply for improvement in surface quality and hole depth during ECD trepanning action [141]. Through broader analysis of previous studies, it can be judged that research fraternity is mainly indulged in evaluating machining performance of ECDD process in comparison to other variants of ECDM. Only a fewer number of studies have shown use of other variants in comparison to ECDD.

2.2 Significant Areas and Ishikawa Diagram: Research trends in the field of ECDM show that there are different areas in which researchers are working to carry out some possible outcomes in this field. These areas may be in terms of some initial inputs, process parameters, in-process identifications and many more. Some of the major areas identified from the literature survey are as shown in figure 3. There are wide variety of influencing parameter that affect the machining performance. These parameters have been taken into consideration in previous studies by different researchers. Through the survey major impacting parameters have been identified and shown by Ishikawa diagram, in figure 4.

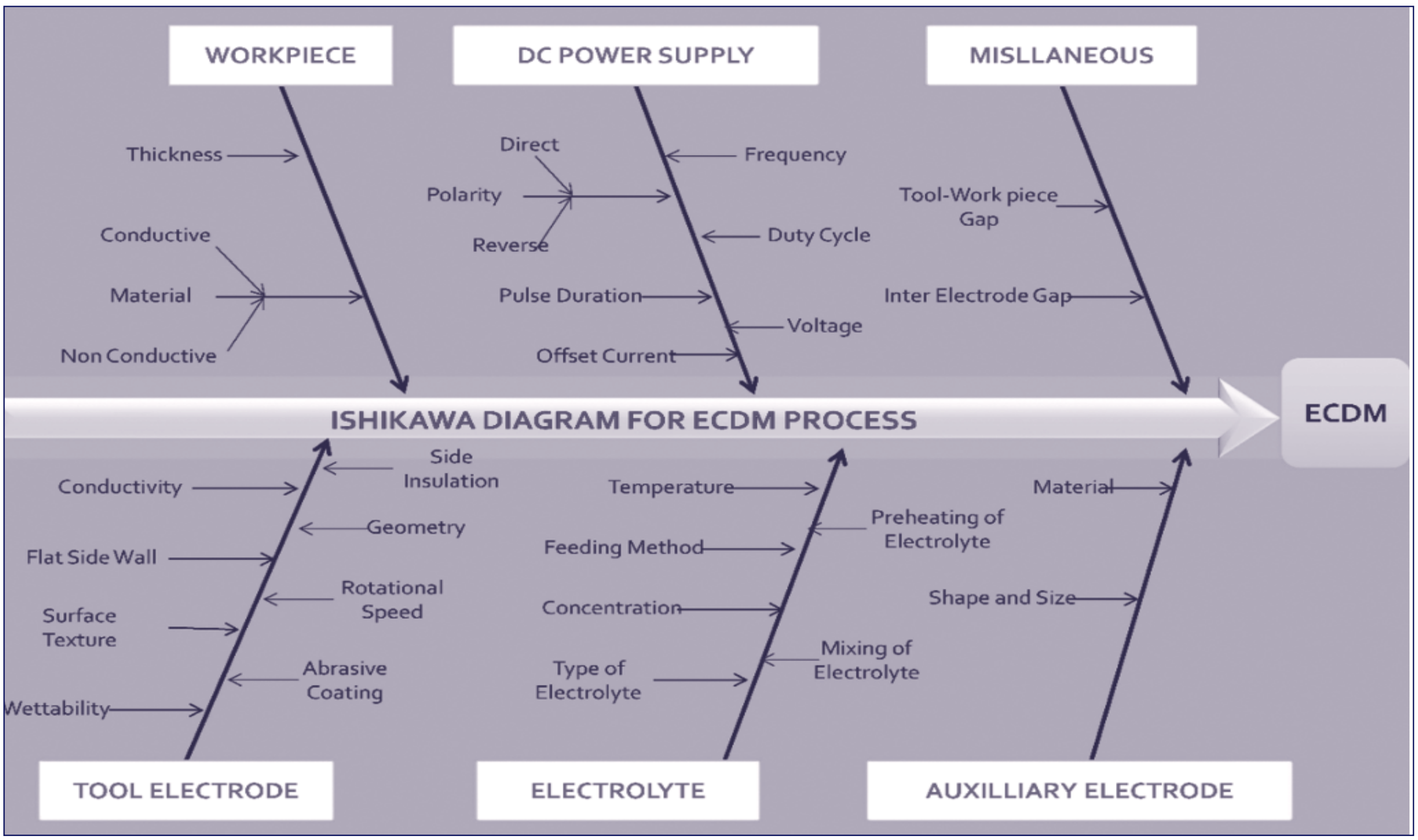
Figure 3. Key Domains of ECDM



2.3 Spark Analysis

A huge number of research have been done in the field of electrochemical discharges (ECD) and this technique is being used for machining of variety of materials as shown in literature survey. However, the phenomenon of machining through electrochemical discharges is still not clear to researchers indulged in this field. Different theories have been presented by researchers for proper understanding of this mechanism. Electric discharge formation at anode tip was initially observed in year 1925, by Taylor [88] and termed it 'anode effect'. After in-depth research in this field for decades, an ECD phenomenon was firstly presented in 1968 [82] and named as 'electrical discharge drilling'. However, the study was not able to explain the spark generation mechanism clearly. A study reported discharge phenomenon as a result of creation of gas layer around the electrode surface [142]respectively. The study reported in this paper explores some of the fundamental processes which occur during ECAM. Experimental apparatus was constructed to enable single pulse discharges to be studied. Results are presented for 200 µs pulses between 2 mm diameter silver steel electrodes in NaNO3 and NaCl electrolytes over a gap range of 10 to 90 µm. Four stages of electrical phenomena were distinguished within a pulse: (a. For identifying these conclusions and better understanding of discharge process, streak photography method was used. However, after all, the study was not able to explain causes of spark or discharge generation during process.

Figure 4. Ishikawa Diagram for ECDM



Furthermore, a study [143] explicitly demonstrated about spark generation mechanism during ECD and proposed a model to estimate peak voltage and current required to begin sparking phenomenon. The study reported spark action as similar to 'switching on/off action' of an electric switch. The study reported that with increment in density of hydrogen bubbles, electrolyte heating could be increased which results in formation of vapor bubbles. These vapor bubbles limit the electrolyte and tool contact by covering the tool surface. Basak and Ghosh [144] extended their study to investigate the ECD phenomenon and revealed that machining performance can be improved by introducing an accompanying inductance in the circuit producing high discharge. A study reported that electric discharges is the result of 'switching phenomenon' between the tool and the electrolyte instead of collapsing the insulating gas layers during ECDM process [48]. In contradiction to switching phenomenon; a research study described about 'Arc discharge valve theory' and stated that each bubble is treated as a valve that is responsible for generation of the spark in form of an arc [145]. They made computations for spark energy and results were obtained for diameter of hydrogen gas bubbles. The study concluded that the purpose of valve theory seems to be realistic showing good agreement with experimental findings. To conclude this theory, it was assumed that the bubbles formation occurs inside the electrolyte tank only upto depth of few millimeters. However, their detailing was not demonstrated regarding arc formation inside the electrolyte solution at deeper depths. Another study [146] reported generation of high current densities at sharp edges of the tool electrode that initiates spark formation.

Further, for observing spark mechanism, 'Precolation theory' was proposed in a study [147] to analyze the development and adherence of bubbles during ECDM process. Wuthrich and Bleuler [148] in their study reported that, spark generation takes place because of coalesce of small bubbles to produce larger bubbles forming gas film around the tool electrode.

3. OUTLOOK OF FUTURE WORK

As the need of machining of variety of materials continues to expand, the researches in this domain are also increasing. Although, the recent studies on ECDM process spread out, the machining process still needs to be enhanced. In order to make ECDM as an effective machining process for variety of conductive and non-conductive materials, lots of related research could be carried out in the future. The following conclusions are drawn in respect of

"The following conclusions are drawn in respect of ECDM to present some futuristic developments and challenges"

In conclusion, ECDM has shown significant potential in comparison to ECM and EDM as an advanced manufacturing technology that offers unique advantages such as high precision, low surface roughness, and the ability to machine complex shapes in difficult-to-cut materials. The study of variants for ECDM has shown that there are multiple approaches to machine the different materials as per the desired dimensions and machining operation. Out of those variables it has been observed from the literature survey that ECDD is the most widely adopted and useful variant of ECDM. The study of variants has also led to a better understanding of the underlying mechanisms of the process, which in turn has facilitated the development of new and innovative techniques for achieving superior machining results. However, there are still challenges to be addressed, such as the need for more accurate and reliable models for predicting machining outcomes, as well as the development of new commercial setups that can withstand the extreme conditions of the process.

Key factors for ECDM have been extensively studied to understand their influence on the process performance. From literature survey researchers have identified various key factors that impact the machining rate, surface finish, and accuracy of the process. Through systematic experimentation and numerical modeling, significant progress has been made in optimizing the machining parameters for achieving better performance and efficiency. However, there are still challenges to overcome in terms of controlling the complex interactions between different machining parameters and their effects on the machining outcomes. Further research is needed to refine the models used to predict the machining performance, and to explore new applications of ECDM in various industries. The sparking action has been extensively used to understand the electrochemical discharge machining process and its mechanisms. However, there is still room for further research and development in terms of improving the accuracy and reliability of sparking action, as well as developing new and advanced methodology.

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