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Electro-Discharge Machining: Recent Developments and Trends

Anbesh Jamwal[1], Ankur Aggarwal[2], Nishant Gautam[3], Akhil Devarapalli[4]

[1,2,3]PG Student, Dept. of Mechanical Engineering, Amity University, Noida, U.P., India
[4]UG Student, Dept. of Mechanical Engineering, Amity University, Noida, U.P., India

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Abstract - *In the present manufacturing scenario, the industrial product not only requires the high precision and quality but should be produced in the minimum time in order to sustain their position in the global market competition. Thus, it is required to regulate the input process parameters for achieving the desired output or the performance. EDM is the most popular machining process in the present time among all the machining processes. EDM is the widely used non-conventional machining process that is capable to machine the hard materials such as alloys, composite and even the ceramics also. EDM has wide range of application in automobile, aerospace, defense and precision engineering industries. In the past years, the many studies have been done to improve the EDM process. This paper reviews the current research trends and recent developments in EDM process and modeling techniques.*

Key Words: Electro-discharge machining, WEDM, Powder additives, Process parameters, Dielectric, optimization techniques.

1. INTRODUCTION

EDM is widely using non-traditional machining process in the present manufacturing scenario. The electro-discharge machining has widely used in the production of dies and molds [1]. Basically, EDM is used to machine those materials which are difficult to machine by the conventional machining process. Finishing parts of aerospace and automobile industries are machined by the EDM process. There is no direct contact between the tool material and work-piece. The material is removed by the thermal erosion in the EDM process [2]. Previously studied on EDM reported that the material removal rates are less in the EDM than the other conventional machining processes. The major advantage of using EDM rather than conventional machining processes is very high surface finish rates. The advantage of using EDM there are no mechanical vibrations and mechanical stresses occurs during machining because of no direct contact between the work-piece and tool material [3]. Another advantage of using EDM over other machining processes that it can machine any profile or geometry. It can easily machine the complicated geometry which can be difficult to machine by some other machining processes [4]. But the limitation is only the tool material and work-piece must be electrically conducted. This is one of the major requirement of the EDM. Generally used tool materials in the EDM are tungsten and copper. The EDM technique is developed in the 1940 by two Russian Scientist B.R Lazarenko and N.I Lazarenko. Later in 1967 the scientists of Soviet Union developed first EDM in which they used wire as the electrode [5-6]. EDM utilizes the electrical energy to generate the electrical spark and the material removal is done by the thermal energy that is generated by the electrical spark [7]. The tool material and work-piece are maintained by a small gap known as spark gap which is 0.005mm-0.05mm [8]. There are the continuously electrical charges occurred between the tool and work-piece in the presence of the dielectric fluid [9]. The dielectric fluid may be the EDM oil and kerosene oil [10]. The main purpose of dielectric fluid is to provide the dielectric medium and flushing out the machining debris from the work table [11]. The major disadvantage of the EDM is the overcutting and the formation of the recast layer [12]. When the DC supply given then the electric spark is generated and the ions starts flowing from the work-piece and electrons from the tool material [13]. The electric field is generated between the work-piece and the tool and it is maximum where the gap between the work-piece and tool is minimum [14]. The recent research is EDM on the composites because composites are widely used in the industries due to their special properties and these are hard in nature [15]. Due to hard in nature they are difficult to machine by conventional machining processes. Current trends in the EDM is carried by researchers on the machining techniques like Dry EDM [16], EDM with additives [17], EDM in water [18] and the different modelling techniques [19] for the better results. These days micro-EDM gains more popularity because it can achieve the surface finish up to micro level [20]. The power consumption is very less in the case of micro-EDM. The material removal rates are very low but the surface finish rates are very high [21]. The tool wear rates are depending upon the polarity [22]. Previous studies show that when the polarity is reverse the tool wear are high and it is less when the polarity is positive [23-24]. These days EDM is using in the industries where the better surface finish is the major requirements [25]. This paper provides the review of various researches carried out in the past on the electro-discharge machining. This paper also aims to the review of various modelling techniques used in the electro-discharge machining and future research directions. Figure 1 shows the all research areas in EDM.

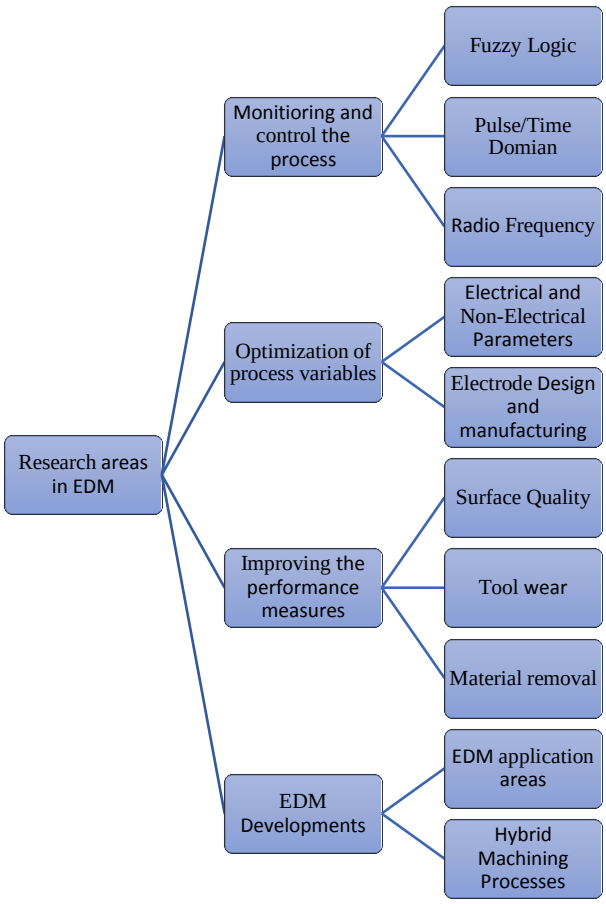

Fig -1: Research Areas in EDM

2. ELECTRO-DISCHARGE MACHINING

EDM is one of the most popular non-traditional or unconventional machining process in the present manufacturing scenario [26]. With the high surface finish rates and ability to machine those material which are difficult to machine by conventional machining processes [27]. This section provides the basics of EDM process and EDM variations which combines other material removal methods.

2.1 EDM Process

Lot of research has been done in the EDM field [28-29]. EDM is one of the earliest un-conventional machining processes. Electro-discharge machining is a thermoelectric process which utilizes the heat energy generated by spark to remove the material from the surface of work-piece [30]. The only limitation in the EDM is that the work-piece and the tool material both should be electrically conductive. The electrical energy converted into the thermal energy by series of the electric discharge that occurred between the work-piece and tool which are immersed into the dielectric fluid [31]. The plasma channel is generated by thermal energy between anode and cathode. The plasma channel is generated at a temperature range of 8000-1200°C [32]. Sometimes it is nearly about 20,000°C which is too high and can machine any material. The location of electric spark which is generated by heat energy is determined by the narrowest gap between the tool and work-piece [33]. Duration for each spark is very short. The frequency for each spark is high as thousands sparks per second. However, spark radius is very small and the temperature in the spark zone is very high [34]. This temperature of spark is capable for partially vaporize and melting the material from both the work-piece and tool material. The volume of material removal per discharge from the work-piece depends upon the specific applications and it is ranging from 10^{-6}-10^{-4} mm^3. The material removed from the surface of work-piece is in the form of craters which is all overspread on the work-piece. Craters sizes is highly influenced by the value of current. Previous studies show that the size of crater is increase with increase in discharge current. Figure 2 shows studies conducted in EDM field.

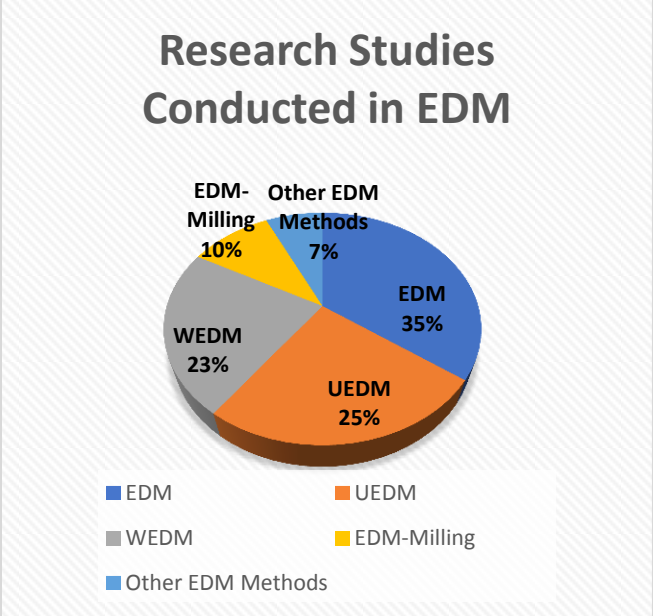

Fig -2: Studies conducted in EDM

2.2 EDM Variations

There are number of EDM variations have emerged in the industries to machine the super hard alloys, composites, aerospace parts and ceramics [35-36].

2.2.1 Wire EDM: WEDM is most widely used in industries these days because of capability to generate complicated shapes and profiles without use of pre-shaped electrode which were required in the basic EDM [37]. The only limitation in the WEDM is same as EDM that the tool material and work-piece both should be electrically conductive. WEDM uses the thin continuously traveling wire that is feeding by the microprocessor through the work-piece. To overcome

the common problems in the conventional and non-conventional machining processes there is development of Hybrid machining processes which involves the EDM with Ultrasonic vibration (USM) [38], Laser beam machining (LBM) [39], High-speed machining (HSM) [40], grinding [41], electrical discharge grinding (EDG) [42] and electrochemical discharge machining (ECDM) [43].

2.2.2 Ultrasonic Vibration: Ultrasonic vibration to the electrode is one of method introduced to improve the machining performance of EDM [44]. It expands the machining area of EDM and helps to improve the machining performance of EDM over the hard materials which are difficult to machine by conventional machining processes [45]. The main advantage of ultrasonic vibration in EDM it improves the dielectric circulation which helps to generate the large amount of pressure between the work-piece and tool material [46]. Another advantage of ultrasonic vibration is it facilitates the debris removal from the work table. The spark erosion which was usually produced by pulse power supply is replaced by the DC supply and the pulse charge is produced by the relative motion between the work-piece material and tool material [47]. It simplifies the equipment and reduce overall cost of equipment. It is found that a new combined technology can be developed with the benefits of both the EDM and ultrasonic machining [48].

2.2.3 Laser Beam Machining: The hybridization of laser beam machining and EDM using in the micro-machining processes to reduce the production time and eliminating the recast layer produced by EDM [49]. Laser beam machining is used to fabricating the desired shape from the material and EDM is used for the final finishing. The machining rate is faster in the hybridization of LAEDM [50]. Nd-YAG laser are commonly used in the LAEDM. Main purpose of EDM is only to provide the finish operations [51]. Production rate, surface finish and efficiency are higher and tool wear rate is very less in the hybridization of LAEDM as compared to conventional EDM and Laser beam machining [52].

2.2.4 High-Speed Machining*:* Comparatively less research has been done in the hybridization of EDM with High-speed machining as compared to other EDM variations. The hybridization of HSM and EDM would give number if benefits [53]. In present time high-speed machining has replaced use of EDM. But for deep cavities, and complicated shapes components having the internal corners and some work-piece materials which are difficult to cut, EDM is still required [54].

2.2.5 Electric Discharge Grinding*:* Electric discharge grinding is the hybrid grinding process works on the same principle as basic EDM. The hybrid grinding capable to machine extremely hard materials which such as carbides 2-3 times faster than the conventional grinding process [55]. EDG capable to achieve high accuracy and high surface finish rates (0.2-0.3µm) than the conventional grinding [56].

2.2.6 Electro-Chemical Discharge Machining*:* Hybridization of EDM and ECM is studied since 1970 [57-58]. ECDM is also known as Electro-erosion dissolution machining process (EEDM). ECDM has wide variety of applications especially in non-conductive materials such as various types of ceramics and composites [59-60].

3. RECENT DEVELOPMENT IN EDM

In the past five years there are lot of studies and developments have been done in the field of EDM still there are research gaps [61-62]. In the past year's lot of developments have been done in the materials and modeling techniques. Lot of research has been done in the composites and ceramics which creates a new research scopes in the EDM [63-64].

3.1 Recent developments in EDM electrode and work-piece materials

In the past few year studies in the material, science has scored the new successes. In the past few decades' strength of ceramic materials has been improved by 100% [65]. Although the outstanding properties of ceramic materials, it is difficult to attain the good surface finish on these materials. In recent years the development of electrically conductive ceramics has made the scope of research in the EDM to achieve the good surface finish rates on ceramic materials [66]. Lot of work have been done on improving the performance of EDM by electrodes. Different tool materials like copper, tungsten carbide, copper tungsten, aluminum and composite based electrodes used for improving the performance of EDM [67]. Copper and graphite are most commonly used tool materials in EDM process. Recent development in the tool materials and selection of optimum machining condition led to very low tool wear rates with high machining efficiency [68]. Electrode material should undergo less tool wear rate when it is affected by the positive ions. Density and melting point of tool material should be high to avoid the tool wear and inaccuracy of tool. Copper electrode material having good EDM wear, good conductivity and good surface finish rates(Ra=0.5µm) with less manufacturability cost. Manufacturing cost of EDM tool material is 50% of total EDM process. Manufacturing cost of EDM tool material can be reduced by powder metallurgy [69-70].

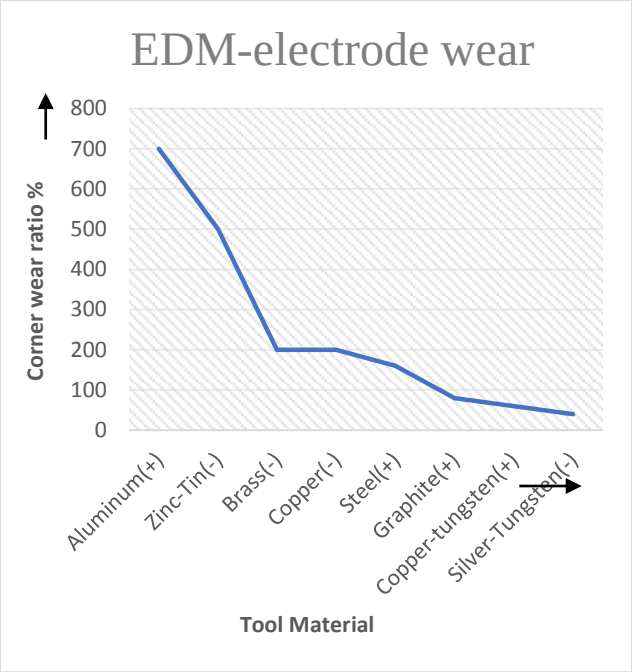

Fig –3. Electrode Wear Ratio with respective tool material

3.2 Responses and its influence parameters

The process parameters help to analyze the effect of the machining performance of any machining process. The performance of EDM depends upon its responses and influence parameters [71-72]. The performance of EDM is depends upon the electrical pulse parameters and rest on the machining conditions. Discharge current and pulse duration are the main electrical pulse parameters which affect the machining performance of EDM [73]. It was found that tool wear rate increase with increase in electrical pulse parameters and tool wear rate is highly influenced by discharge current. Surface finish depends upon the discharge current and pulse duration [74].

The major process parameters of the EDM process are shown below:

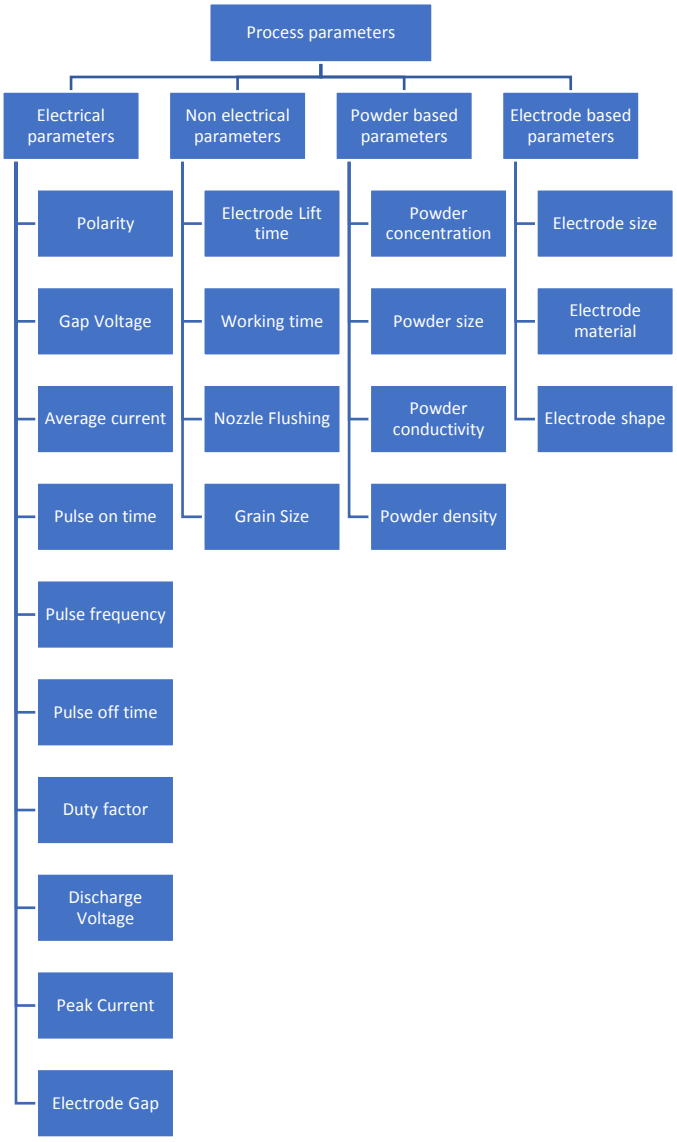

Fig -4. Major EDM Process Parameters

3.3 Effect of Electrical parameters

In EDM it is difficult to explain the effect of all electrical parameters on the individual performance measure. This section describes about the various electrical parameters which affect the performance of EDM.

3.3.1 Effect of peak current*:* To investigate the effect of peak current in EDM on MRR and surface roughness pulse on time varied and other parameters like pulse off time, voltage and wire feed rate kept constant. The material removal rate is slow at low values of current and it is nearly constant as the values of current are low [75-76]. The material removal rate of material starts increasing the value of current increasing [77-78].

3.3.2 Effect of pulse-on-time*:* To observe the effect of pulse-on-time on the EDM performance peak current is varied while the other parameters like pulse-off-time, voltage and wire feed rate kept constant. It is observed that the MRR is increasing with the pulse-on-time at all the values of current and surface quality of material starts decreasing when there is an increase in the value of pulse-on-time [79-80]. Optimum values of surface roughness can be found at the lower value of pulse-on-time and current [81].

3.3.3 Effect of pulse-off-time: It is found that MRR starts decreasing when there is an increase in the values of pulse-off-time. Long pulse-off-time makes a cooling effect on both the electrode and the work-piece material hence results in decreasing the cutting speed and EDM performance degradation [82-83]. Surface roughness improves with the higher values of pulse-off-time. It was also found in some studies that first the surface roughness decreasing with the pulse-off-time then starts increasing when there is an increase in the values of pulse-off-time [84-85].

3.3.4 Effect of servo voltage*:* The effect of servo voltage on the performance of EDM is observed by varying the pulse duration and kept constant all other parameters. MRR starts increasing with increase in the servo voltage initially. But then starts decreasing with increase in the servo-voltage [86-87]. On other hand surface quality of material also starts decreasing with increase in the voltage [88-89].

3.4 Effect of Non-electrical parameters

In addition, the non-electrical parameters such as rotation of work-piece, rotation of tool material and flushing of dielectric fluid also plays an important role for achieving the optimal performance measures of EDM.

3.4.1 Effect of dielectric flushing*:* Dielectric flushing affects the performance measures of EDM. During the roughing operations, flushing of dielectric fluid affects the tool wear rate and electrode wear rate while during the finishing operations it affects the surface roughness [90-91]. In addition, different properties of dielectric fluids also play a vital role in the performance of EDM. It was found in the studies the kerosene oil with additives provides the excellent EDM performance and high MRR and low electrode wear rate can be achieved without formation of any metal carbide on the surface of work-piece [92-93]. The flushing methods can classify into Normal flow flushing [94], Jet flow flushing [95], Immersion flow flushing [96] and reverse flow flushing [97-98]. Some researchers applied the magnetic field to move the debris from the gap and some applied the forced vibrations to move the machining debris from the gap between tool material and work-piece [99].

3.4.2 Effect of rotational movement of tool material*:* Besides the dielectric flushing effect on the performance of EDM, the rotational movement of tool material also affects the performance measures of EDM. Better surface quality and material removal rate be achieved by the applying the rotational movement of tool material over the work-piece by improving the circulation of dielectric fluid in the spark gap [100-101].

3.4.3 Effect of rotational movement of work-piece material*:* Rotational movement of work-piece material in EDM improves the performance measures of EDM in terms of surface quality and material removal rate [102-103]. The rotation of work-piece improves the dielectric flushing over the work-piece which results in the better surface quality and low electrode wear rate and High material removal rates [104]. Still, these non-electrical parameters need further study.

3.5 Powder additives

The performance of EDM can be improved by addition of powder additives. Fine abrasive powder particles are mixed in dielectric fluid which utilize the low pulse energy and increase the spark gap between the electrode and the work-piece. This hybrid process is called powder mixed-EDM. The surface quality and MRR can be increased by the powder mixed-EDM. Too high and too low concentration of powder in EDM oil reduces the machining performance of EDM [105-106].

3.6 Material Removal Rate

In the EDM process material removal takes place from both tool material and work-piece. The material removal rate depends upon the work-piece material, tool material and machining variables. Materials having low melting point having high material removal rate and hence lower surface finish [107-108]. It is found that with increase in pulse current and constant pulse-on-time material removal rates increases but it affects the surface finish of material [109]. EDM efficiency can be increased by supplying the oxygen gas between the spark gap and stack removal rate can be increased by increasing the volume of discharge crater and regular occurrence of discharges [110]. Optimum values for material removal rate can be achieved at low values of current [111].

3.7 Surface roughness

Surface finish is primary aim of machining in EDM. In CMC's pulse on time is most dominant factor which affects the surface roughness. It is also found that surface roughness increases with increase in discharge current and pulse on time [112]. Better surface finish with no surface cracks can be achieved at low values of current [113]. An experiment to obtain the good surface finish in view of Die-sinking EDM and concluded that

surface finish of work-piece is highly influenced by discharge energy [114]. It is observed that at lower discharge energy good surface quality can be achieved [115].

3.8 EDM process development

Since EDM process is non-linear nature, still it requires lot of improvements. Lot of research has been done on the process development of EDM [116-117]. Many authors have discussed about the recent trends and development in the EDM process. Optimization of process variables, modeling techniques, control of sparking process, monitoring and performance measures in EDM process still needs further study [118]. There is need of controlling the process parameters of EDM to enhance the machining process. The development of new technologies for achieving the high surface quality is the major research trend in the EDM [119]. It is observed that most of the research work in EDM is concentrated on improving the surface quality with mixing the powder in the dielectric medium. In many applications, traditional machining operations like milling is replaced by EDM process [120]. Mechanical stresses don't induce in EDM during machining operations this helps in manufacturing of complex shapes [121]. There are several experiments done with electrode of diameter 50µm and multi-electrode for the production of micro-parts by the batch production which reduces the fabricating cost and production time for both the parts and electrodes [122].

3.9 Micro-EDM

Production of smaller size and 3D shape products given a new research scope in micro-EDM field. Micro-EDM is not only capable to machine micro-holes up to 5µm but also machine complex 3D shapes [123]. Micro-EDM process is unlike conventional mechanical drilling which can produces the holes up to 70µm or the other unconventional machining like laser beam which can produce up to 40µm [124]. Elimination of conventional boring or drilling operation is eliminated while performing the EDM operation by the trajectory EDM technique in which tool material is move along with a smooth trajectory [125-126]. There are some other attempts made on EDM trajectory but there is need of complex mechanism or special apparatus to develop the trajectory motion of EDM tool material [127].

3.10 Composites and ceramics materials

The development in composites and ceramics materials in last decades has expand the application area of EDM [128]. Due to better material properties like Hardness, tensile strength and wear resistance it is difficult to machine these materials with conventional machining processes. Composites are widely used in cutting tools these days [129]. Al_2O_3 based composite ceramics which having the good wear resistance and chemical stability properties which make them suitable for use as the modern cutting tools [130]. It is difficult to machine these materials by conventional machining processes. Machining and achieving high surface finish rates on these materials is possible with EDM [131-132].

4. OPTIMIZATION TECHNIQUES USED IN EDM PROCESS

4.1 Grey relational analysis

The grey theory is firstly introduced by Deng in 1982. This theory is useful for dealing with the poor and incomplete information [133-134]. The Grey theory is very effective technique and requires very limited information for the estimation of the behavior of the discrete data problem and uncertainty system. In the Grey theory, there are three types of systems which are Black (No information), white (all information) and grey system (imperfect information) which requires very limited information to estimate the behavior of the problem [135-136]. The data processing range is 0 to 1 in this system and in the data, is distorted to comparable sequence in the normalization. There are three conditions of normalization which are:

a) Higher is better
b) Lower is better
c) Normal is best

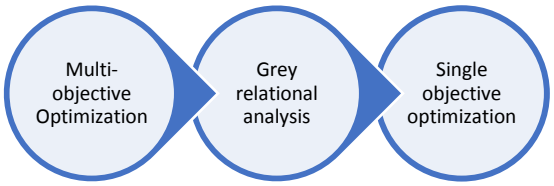

Fig -5. Grey Relational Analysis

4.2 Neural Network

Neural network is a system which is capable to receive, store and apply the knowledge that is gained by experience [137]. Artificial neural network is a flexible modeling tool which is capable to learn the mapping between the input and output parameters of a process which helps in solving the non-linear problems using the software computing methods [138]. An artificial neural network is a model which runs like human brain [139]. It is used to solve the complex problems whose analytical and numerical solutions are very tough [140]. Generally, the neural network design having the three steps which are: configuration how layers be connected and organized, learning how information is stored and generalization how neural network produces the

reasonable outputs for the inputs which are not found in the training. ANN model is based upon some assumptions:

a) Information in the ANN is processed at many simple elements called neurons.

b) Signal is passed between the over connection links and neurons.

c) Each connection link having the associated weight.

d) Each neuron applies an activation function which is non-linear to its net input which helps to determine its output signal.

The multilayer neural networks are formed with numerous neurons having the parallel connection between them and they are jointed in several layers. The structure of the NN contains the input data, number of hidden layers which contains the numerous neurons in each layer and the external layer which is connected the neurons to output.

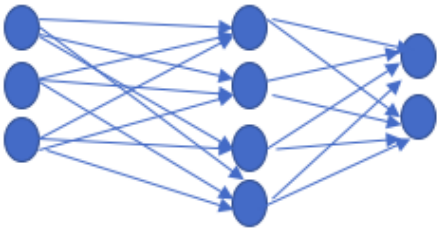

Fig -6. Artificial Neural Network

4.3 Genetic algorithm

The genetic algorithm is a higher-level procedure that is developed for providing the sufficiently good solutions to an optimization problem. In the last few years, GA has made some new research scopes in the optimization field [141]. GA is inspired by process of natural process of selection of large class of evolutionary algorithms. GA are commonly used to generate the high quality of solutions for the many optimization problems in present time [142]. Some researchers have investigated GA application in the electro-discharge machining and used the multi-goal optimization approach [143-144]. There are few steps which are required to apply GA in optimization of machining process.

a) The process parameters or the input parameters are encoded as genes by the binary encoding.

b) A chromosome is formed by the combination of the genes.

c) Crossover is one of the most important operation which is helps in generating the new offspring by exchanging of some parts of two genes. It is very helpful when searching the whole space rapidly.

d) Mutation is also a process which is applied to provide a small randomness to a new chromosome.

e) The encoding process is done to evaluate each of chromosome.

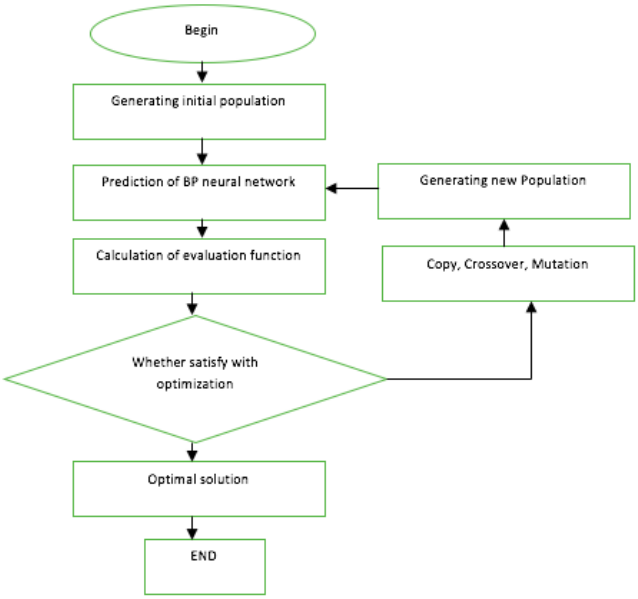

Fig -7. The Solution Procedure of GA

4.4 Finite element method

FEM is a powerful tool that is used for obtaining the real engineering problems. FEM can handle a wide range of engineering problems. Powerful software is required to develop the FEM-based PMEDM model which can be able to consider all aspects of the EDM process [145-146]. ANSYS is one of the powerful tool that can be used in the FEM analysis. Any complex geometry can be easily analyzed using ANSYS tool. Many researchers have done work on modeling and simulation of results for Powder mixed EDM [147-148]. Using the boundaries condition the geometry of work is created and different kind of load applied on the work domain. Mapped meshing technique is used for meshing of workpiece [149].

4.5 Artificial bee colony optimization

In the last few years' advancement in the EDM process has given new research scopes. These new research scopes have given some new optimization techniques also. Artificial bee colony optimization was

proposed by Karaboga in 2005 [150]. ABC optimization is inspired by the foraging behavior of honey bees. In the ABC optimization colony of artificial bees contains generally two groups that are unlooker bees or unemployed bees and employed bees. In which the employed bees have idea about the food source (nectar position) and quality of food (nectar amount). Whereas the unemployed bees are get the information of food source form the employed bees and they are attracted towards the food source and becomes employed bees [151]. Once the food source is consumed then employed bees becomes scout bees and starts finding new food source. In the ABC analysis number of employed bees is always equal to unemployed bees in the population. Presently the ABC analysis is used to solving the continual optimization problems [152]. The structure of artificial bee colony optimization is shown the figure below:

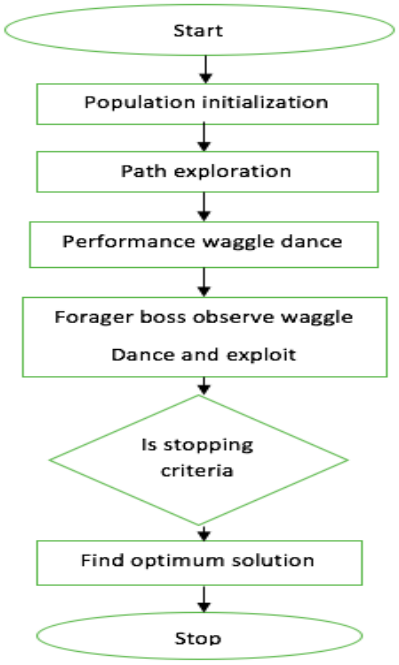

Fig -8. Procedure of Bee Colony Optimization

4.6 Fuzzy set theory

Fuzzy logic is introduced by Lotfi Zadeh and Dieter Klaua in 1965, Fuzzy logic is a mathematical theory that allows a user to model the reasoning process of human in the linguistic terms [153-154]. The values of fuzzy are determined by the membership functions that define the degree of membership of a particular object in the fuzzy set. Fuzzy rules are used to build up the relationship between the inputs and output in a fuzzy model that are characterized by a set of the linguistic statements [155]. The number of fuzzy rules in a particular fuzzy system is related to the number of the fuzzy sets for each of the input variables. Fuzzy operators and the fuzzy sets are the verbs and subjects of the fuzzy logic [156]. IF-THEN rules are used to make fuzzy logic useful. The output of the fuzzy process needs to be single scalar quantity. De- fuzzification is the process of the conversion of fuzzy quantity into the scalar quantity [157].

5. CONCLUSION

EDM is one of the widely used unconventional machining method that is capable of producing the complex shapes. The only limitation in the EDM is the work piece should be conductive in nature. With the time there is lot of improvements in the EDM and its assisted processes as well as optimization techniques, which made some new research scopes in the EDM. Some studies found that non-electrical parameters also play an important role in the performance of the EDM. Developments in modeling techniques have made new research scopes in the EDM and improves the performance of EDM process. Based on the various research work presented the following observations are made on the basis of this review work.

a) In this review paper, there is collection of various research work in the field of assisted EDM process developments which have been developed to provide the better surface finish and good quality products at the lower cost.

b) It is found that both the electrical and non-electrical parameters play an important role in the performance of EDM process but some studies reported that non-electrical parameters are main parameters which affects the surface quality of the product.

c) It is also found that there are lots of improvement in the optimization techniques but the objective is same for all the optimization techniques to improve the EDM performance, to get the desired output from the input and to develop some new hybrid techniques to machine new materials under the better working conditions.

d) Through the recent developments and optimization techniques used in the EDM processes minimize the tool wear rate, maximize the material removal rate and improves the surface quality.

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BIOGRAPHIES

Anbesh Jamwal received his B. Tech in Mechanical Engineering (2016) from SRM university, Chennai and pursuing M. Tech in Industrial and production engineering from Amity University, Noida. His research interests include Lean manufacturing, Agile manufacturing, machining processes and composite Non-Traditional materials.

Ankur Aggarwal is M.Tech. (Industrial and Production Engineering) student in Amity University, Uttar Pradesh. He has passed his B.Tech. in Mechanical Engineering from Uttar Pradesh Technical University, India in 2014. His area of expertise is Advanced Manufacturing Processes, Lean, Green and Agile Manufacturing System.

Nishant Gautam did his B. Tech in Mechanical Engineering (2015) from GEC College (Jabalpur, M.P.) and is pursuing M. Tech in Industrial and production engineering from Amity University, Noida. His research is in Non-Traditional machining processes and Manufacturing Technology.

Akhil Devarapalli is currently pursuing B. Tech in Mechanical Engineering and Automation from Amity University, Noida, Uttar Pradesh, India.