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A review on optimization of machining performances and recent developments in electro discharge machining

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Abstract. Electro discharge machining (EDM) is a popular unconventional machining process widely employed in die-making industries. Careful selection of process parameters such as pulse current, voltage, on and off time, etc. is essential for machining of hard and conductive materials using EDM. Previous researchers working in the area of EDM have extensively analyzed the machining performance through experimental study, modeling, and simulation and also by theoretical analysis. This article discusses the significant summary of the work performed by earlier researchers through a detailed literature survey. Relevant literature on EDM and impact of process parameters on performance measures such as surface quality, tool wear rate and material removal rate are reviewed. The challenge and limitation of EDM process are also highlighted in this article. It is observed that optimization of process parameters is essentially required for effective and economical machining. So, this article addresses the various issues related to EDM and also provides brief insight into some of the current generation applications of EDM process explored in various industries.

Keywords: Electrical discharge machining / material removal rate / surface quality / tool wear rate

1 Introduction

In the present-day scenario, there has been incessant growth of accessibility and application of difficult-to-machine materials. Various nontraditional approaches have been explored and adopted to machine these materials. Electrical discharge machining (EDM) is one of the suitable processes broadly applied for the machining of electrically conductive materials regardless of its hardness, strength, etc. In this machining process, combined electrical and thermal energy is used in terms of controlled erosion through a sequence of electrical spark generation to remove the material from specimen [1]. The cornerstone of this EDM process was laid in 1770, when Dr. Joseph Priestly revealed the continuous erosive results obtained from the series of sparks. It was primarily presented by Dr. B.R. Lazarenko and Dr. N.I. Lazarenko in 1943, in which spark generator used was recognized as the Lazarenko circuit. Later on in 1950, Lazarenko developed EDM system having power supply controlled with resistance–capacitance (RC) circuit. Afterward, in 1960, the modified EDM was the combination of pulse and solid-state generators that not only reduced earlier difficulties using weak electrode but also originated orbiting systems. The EDM developed in the 1970s used less number of electrodes to create cavities. In 1980, a computer-assisted EDM called computer numerical controlled EDM was invented in the United States [2,3]. Since then, EDM process has attracted worldwide attention as a technique to machine various advanced conductive materials such as carbide, composite, and ceramics. It is also used for the manufacturing of mould, die, automotive parts, aerospace parts, surgical apparatus, etc. Due to noncontact surface between the specimen and the tool, thin and fragile samples could be machined without damage [4].

Keeping the potential utility of this process in consideration, there is burgeoning requirement of summarized literature at one place wherein description of essential machining parameters along with the current trends would be discussed. Therefore, this article is an attempt to serve the aforementioned purpose and presents a systematic review on the machining parameters for efficient EDM performance.

In nutshell, the article reviews the work performed on the measurement of various EDM performance and EDM operating parameters, along with the review on the current state-of-the-art work on EDM-based research as the concluding part of this article.

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2 Major areas of EDM research

This section describes the major areas related to EDM-based work. The first section provides the study related to the mechanism of EDM machining performance measures such as material removal rate (MRR), tool wear rate (TWR), and surface quality (SQ). The second section reports the experimental improvement of process parameters which are essential to optimize the performance measures. The third part includes the research regarding the modeling and optimization of both process parameter and performance measurement.

2.1 EDM performance measures

Several research works have been discussed which provide optimization of EDM performance measures such as high MRR, low TWR, and suitable SQ. This section studies each of the performance measures and the methods for their improvement.

2.1.1 Material removal rate

2.1.1.1 Material removal mechanism

The EDM process removes material by thermal energy. The temperature at the spark zone is actually high enough to vaporize the material. Thermal energy is provided by electricity flowing between the tool and workpiece in the form of a spark. Amperes are used to denote the amount of electricity used in the machining process. Increasing the amperes also increases the amount of material removed [5]. Material removal of the specimen is calculated from percentage of mass loss per machining time. This observation along with measurement determines the MRR at every recommended time throughout the EDM experiments. With EDM parameters in correlation with machinability factors, namely, MRR and EW, it was found that the lower current is meant for small electrode, whereas larger current is required for big electrode. The percentage of mass loss increases with increase in machining time because of loss of heat energy generated to air and dielectric fluid, fragments development along with expulsion, and carbon deposition in addition to vibration of electrode [6]. An experimental progress of machining effect of single silicon crystal can be achieved using ohmic contact which leads to decrease in the contact resistance between single silicon crystal and metal electric feeder. During machining of p-type silicon, discharge occurs only when p-type silicon is arranged at positive polarity. On the other hand, in the machining of n-type silicon, machining rate is larger at negative polarity of n-type silicon [7].While EDM is performed with different tool shape, it was observed that longer pulse on-time is nonlinearly related with material removal rate which in turn causes more chopping on the gap time duration, making it short. It was also investigated that material removal rate linearly improves with pulse off-time as correct flushing of debris but TWR decreases linearly due to increase tool area. Among the various tool shapes, circular tool is preferred due to its high MRR and low tool wear (TW) [8]. During machining, positive polarity shows more MRR than negative polarity due to heavy and larger positive ions. Its bombardment effect in the discharge channel accelerated with long pulse duration [9]. The electromagnetic force linearly increases with MRR due to ejection of debris from inter-electrode gap and the migration of negative charge and electrons forms plasma channel. But after certain point MRR decreases because more machined debris accumulated in the gap leads to abnormal discharge and open circuiting. It was also revealed that nonlinear nature of SR resulted in normal discharge and no remelting and clogging of debris formation on EDMed surface gave the appearance of good surface finish [10]. In EDM machining, the gap width is selected with various process parameters, namely, pulse on-time, duty cycle, current, ignition voltage effects on flushing, measurable stock removal, and wear rate. It was reported that the beginning of discharge due to evaporation of tiny particle bridges (metallic, organic, or gaseous) occurred with increase in current. In addition, it was also found that foreign particle-infected liquid shows the change in the conductivity. Therefore, an optimized discharge condition can be suitable for effective and stable machining process [11].

2.1.1.2 Methods of improving material removal rate

Various arrangements have been explored for improving material removal rate. The effect of ultrasonic-assisted EDM offers significant advantage compared with conventional EDM in the form of MRR, SR, relative electrode wear (REW), and machined hole on several materials, namely, magnesium alloy using titanium carbide particle in dielectric fluid, etc. It is experimentally found that ultrasonic-assisted EDM has more MRR, SR, and REW with rise in the peak current. Surface modification as well as wear resistance in combined EDM is comparatively more than in conventional EDM because of titanium carbide particle [12]. The ultrasonic vibrated tool assisted with electrode discharge machining had more MRR than conventional EDM considering the dependency of small pulse duration and low discharge current, better flushing, easy ionization, high rate of pressure drop, and cavitations [13]. During electro-discharge abrasive drilling (EDAD) of tungsten carbide P20 and mold steel HPM 50 using metal matrix composite rotary electrode, it was reported that the MRR and front gap maintain linear relation with current. The machining of composites using uncoated SiCp electrode results in lower tensile strength than that of machining of composites with electroless copper-plated SiCp electrode. While comparing the MRR obtained during the EDAD of mold steel HPM 50 using rotating composite electrodes and pure electrode, it was found that rotating composite electrode shows lower MRR but pure electrode is capable to produce more MRR. Overall, the EDAD showed better MRR and SR than EDM [14]. Comparative performance of multispark EDM and conventional EDM were also investigated while considering MRR,TWR, SR along with energy consumption. A multispark EDM offers more desirable result in terms of more MRR, low TWR, and efficient energy with negligible SR than the conventional EDM [15]. The proper addition of powder particle with dielectric fluid improves MRR and decreases TWR during machining of powder metallurgy-EDM (P-EDM) which happens due to less thermal conductivity and largest spark gap of powder particle. The spark gap increases with increase in the appropriate amount of powder particle. It was noted that copper powder does not have such significant MRR because of its high density [16].

An attempt is made to improve the MRR and SR using low-frequency vibration-aided EDM upon stainless steel. The lower amplitude and vibration of the sample provide more stable and better flushing effect which induces more MRR, whereas low-frequency vibration results in better SR and low TW [17]. While performing the EDM of austenite ductile iron (ADI) material with saw-shaped electrode, the use of semi-empirical expression and pitch electrode confirmed the more MRR and poor SR [18]. A nonlinear relationship had been discussed among MRR, EWR with powder concentration, pulse current, and pulse on-time [19]. While comparing the process parameters of machined ceramic composite materials, the disadvantage of silicon- and aluminum-based ceramic composite over ZrO_2-TiN machined surface in terms of crack formation was observed. Silicon- and aluminum-based ceramic composite showed crack on surface after machining due to spalling effect, whereas ZrO_2-TiN machined surface does not show spalling effect due to higher fracture toughness [20]. A strategic EDM had been manufactured to produce the ceramic components using composites. In addition, it is authenticated with the fabrication of a high-temperature mesoscopic gas turbine. It was observed that decrease in discharge input causes linearly decrease in the pulse shape, MRR, SR, and sparking gap size, but improves EW. Furthermore, the chemical reaction in EDM causes higher machining speed and lower TW [21]. In EDM machining, the material removal and thermal shock damage of machined surface of specimen had been investigated using water as dielectric. From this experiment, improvement of MRR was observed that resulted from the rise in the discharge current and working voltage. But it decreases with increase in pulse duration. The thermal shock induces cracks and loose grains in surface cause damage and reduce the strength of product. It was also noted that ceramic sample showed good damage tolerance capacity and higher Weibull modulus over brittle ceramic [22]. While comparing ZrB_2-40 wt.%. Cu composite electrode with Cu electrode, it was found that ZrB_2-40 wt.% Cu electrode offers additional desirable MRR and low tool removal rate (TRR), but diametrical overcut along with average SR is very negligible. The MRR and TRR increases due to combined properties of wear resistance, electrical and thermal conductivity of 40 wt.% Cu [23]. In P-EDM, copper electrode with aluminum powder suspended in the dielectric showed more MRR, whereas graphite powder showed low MRR but improved surface finish. The high carbon high chromium sample revealed best machining and surface finish in remarkable combination of copper electrode and graphite powder [24]. In a recent study, the machining of three samples, namely, aluminum, mild steel, and tool steel, were discussed. Aluminum showed more relative emission rate with low peak current because of its low melting point and high heat conductivity. The mild steel and tool steel showed small improvement of relative emission rate with peak current increasing with vaporization of melted sample. It was also noticed that aerosol emission is inversely proportional to die electric level above due to more melted vapor. It was pointed out that increase in dielectric level decreases MRR [25]. From the machining of tool steel, it was highlighted that the current in the gap increases which results in the increase of MRR, whereas SR decreases with increase of pulse on-time. In addition, overcut shows nonlinear with increase of spark gap [26].

Relative study has also been performed between rotational EDM and conventional EDM, which shows that the MRR is directly proportional to pulse current due to more spark energy. The nonlinear nature behavior between pulse on-time and MRR due to low-energy transfer to specimen was also observed. In addition, MRR of rotational EDM decreases than in traditional EDM due to breakdown resistance of dielectric. The rotational spark provides better surface finish in comparison with traditional spark because of small void formation on specimen surface. The rotational tool showed low TWR in comparison with traditional tool [27]. During the comparative study of various EDM, it was noticed that ultrasonic-assisted cryogenically cooled EDM (UACEDM) provides lower EW and SR and more MRR in comparison with conventional EDM. It was observed MRR is directly proportional to pulse on-time and duty cycle because of resolidification of some melt material at low discharge energy applied on sample. Conventional EDM provides high EWR, MRR, and SR with increase in discharge current compared with other two EDM due to formation of recast layer [28].

An integrated methodology taking into account the Taguchi L9 orthogonal array and Grey relational had been used to optimize machining parameters for machining of special stainless steel. During machining, single discharge energy becomes large causing increase in MRR and SR [29]. The higher MRR could be obtained with selection of larger current intensities and duty cycle, whereas lower SR could be obtained by setting short pulse duration and high discharge current which forms small crater [30]. A developed modular piezo-unit for inducing longitudinal vibration on tool is used for improving flushing condition and process stability and reducing total process time for producing seal slot on specimen during EDM. Moreover, MRR is improved by 11% and relative tool electrode wear by 21%. In addition, the high vibration frequency and low amplitudes could improve machining efficiency [31].

The EDM-based machining of two gamma titanium aluminides 45XD and GE 48-2-2 revealed that average discharge current has better effect on MRR than open-circuit voltage [32]. The remarkable combination of visual and electrical information of the gap phenomena in quasi-real steady-state erosion condition was measured by sinking EDM. At constant pause duration and at the actual erosion state, most of the microcavity was filled with gas bubble(s) that leads to the metallic phase discharge. The lateral spark of EDM and negligible impulsion on spark location makes it suitable for low MRR [33]. An optimized TW of different graphite electrodes in EDM can be established by considering intelligent process control. The measurement of TW of graphite was difficult because of its porous nature and more weight. The MRR is directly proportional to spark energy, whereas it is inversely proportional to pulse duration due to less effect of plasma channel expansion [34]. The MRR increases with increasing discharge current as well as pulse on-time to certain point due to more spark energy that leads to more vaporization and melting of metal of EDMed surface. The MRR increases with increase of pulse off-time and decrease of voltage because the narrow plasma channel results in less energy transfer to machined surface. Extreme increase of discharge current due to formation of larger crater on the machined surface offers more SR [35]. During EDM of steel, MRR showed linear relationship with both peak current and pulse on-time:

$$\mathrm{MRR}(\mathrm{mm}^3/\mathrm{min}) = \frac{W_i - W_f}{7.8 \times t} \times 100, \tag{1}$$

where W_i and W_f are the weight of specimen before and after the machining, t represents the machining time, and density of steel is $7.8\,\mathrm{g/cm}^3$.

It was also reported that increase of pulse off-time does not show much effect on both MRR and SR [36]. Use of P-EDM for die steel showed that MRR increases due to increase in pulse current but decreases with increase of pulse on-time due to expansion of plasma channel. The EWR increases with increasing peak current for positive polarity and it decreases with increasing peak current for negative polarity. The EWR decreases with increase in pulse on time for positive polarity but it improves with increase in pulse on-time for negative polarity [37].

Nowadays, EDM is used in mould and die industries for manufacturing of electrical, automobile, and household products using kerosene as dielectric. The use of kerosene is more harmful and waste as compared to distilled water and dry EDM [38]. The MRR with lower value of no-load voltage along with peak current improves machined surface. The MRR and EWR are linearly increased with peak current. The modified layer thickness increased with the elapsed working time and pulse duration and decreased with no-load voltage increase due to transfer of more electrical discharge energy to machining surface. The high-corrosion-resistance EDMed surface could be achieved with copper–tungsten electrode due to the exceptional presence of tungsten particle in comparison to copper electrode [39]. The effect of ohmic contact between p- and n-type silicon wafers shows that machining rate increases by changing rectifying contact to ohmic contact, which in turn improves EDM efficiency [40]. An operation for EDM in terms of machining time had been calculated and validated along with industrial application. The time estimation was reliant on reference values for material removal or machining time which resulted from machine calibration procedure [41]. A comparative study was made on nanopowder mixed EDM(NPMEDM) and conventional EDM with silver-coated copper electrode in machining of Inconel 800. It was observed that the NPMEDM decreased the TWR, SR, and MRR than the conventional EDM using aluminum, silicon, and multiwall carbon nanotube powder in NPMEDM, respectively [42].

2.1.2 Tool wear rate

2.1.2.1 Tool wear rate mechanism

The tool wear process is similar in nature to material removal method as both specimen and tool are used as electrodes in EDM. Electrode or tool wear is obtained from bombardment of either electron or positive ion. At positive electrode, the EW is produced due to bombardment of electrons. At negative electrode, the EW is produced due to bombardment of positive ions. As negative or positive ions collide into the electrode surface, heat is generated. The heat vaporizes the electrode material and a small amount of electrode material is removed with each spark. This removal of material is known as electrode wear [5]. During the machining of metal matrix composite, the extreme thermal loading and high discharge current of EDM resulted in high MRR. The shielding effect and more quantity of titanium carbide particle in dielectric fluid showed decrease in MRR.

The tool wear rate is

$$\mathrm{TWR}\,(\mathrm{mm}^3/\mathrm{min}) = \frac{W_{\mathrm{tb}} - W_{\mathrm{ta}}}{t}, \tag{2}$$

where W_{tb} and W_{ta} represent for weights of tool previous to and later than the machining, t is the machining time. A percentage variation of titanium carbide particle in sample was found to be inversely proportional to EWR due to higher electrical resistance and it was directly proportional to the recast layer thickness [43]. A black layer formed on electrode surface was composition of migrated material from workpiece and dielectric fluid. In addition, black layer composition changes thermal conductivity of surface of copper–tungsten electrode resulting in increase of EWR [44]. The black layer in EDM is composed of carbon and iron. It was found that equivalent carbon is smaller in beginning and gradually increase in amount. This black layer reduces EW [45]. The vapor density of tool measurement in the arc plasma is performed using single pulse discharge under various thickness of carbon layer deposited on the tool surface. The positive polarity of copper electrode and lower amount of carbon deposited under short pulse duration resulted in high tool EWR [46].

2.1.2.2 Method of improving tool wear rate

The dry EDM of specimen revealed drastic reduction in tool EWR along with extremely high MRR at negative polarity of the tool compared with positive polarity of tool electrode. In dry EDM, the material per pulse discharge increases due to molten workpiece at discharge area separated with no reattachment to electrode surface. The TW in air EDM is zero and independent of pulse duration [47]. The better EW in machining was obtained with supply of low current. A cylindrical copper electrode in machining was preferred as it did not require redressing

[48]. An integrated pulse generator consisting of arc pulse and auxiliary circuit was used to predict machining efficiency while shutting off the dangerous pulse and applying sweep pulse. It was observed that shutting off harmful pulses increases the machining performance and decreases the TW rate. The use of sweep pulses also improves machining efficiency and increases the tool wear rate than shutting off harmful pulses [49]. The performance of multihole electrode such as copper chromium and aluminum were used in EDM machining of steel. The depth of cut increases due to increased current using aluminum electrode, whereas it remains constant with the use of copper chromium electrode. The hardness of machined specimen was more for aluminum as compared to copper chromium electrode. The copper chromium electrode generates less EW and good MRR as compared to aluminum electrode [50].

When performance of copper and graphite electrode was compared, it was noted that copper electrode offers more desirable results in terms of less EW than brass electrode due to its high thermal conductivity and melting point. The highest wear ratio was observed using brass electrode due to its low thermal conductivity and low melting point. In an overall performance, it was also reported that wear ratio and MRR increase with increasing current and gap voltage [51]. A comparative study of 316L and 17-4 PH stainless steel using copper electrode showed that MRR and surface finish of 316 L stainless steel were better because of more spark energy and impulsive force in interelectrode gap. It was also reported that EW of copper electrode is directly proportional to pulse current because of its low melting point, whereas EW of copper tungsten electrode is low because of its high resistance to spark. The copper tungsten electrode offers more desirable surface finish over graphite electrode [52].

Sometimes MRR is not only increased with increase of current but also with pulse on-time compared to increase in pulse off-time. The TWR increases with increase in the pulse off-time and current, but it decreases with increase in pulse on-time. The SR increases with increase in current and pulse on-time, but it decreases with increase in pulse off-time [53]. On the contrary, in a recent study, the MRR is directly proportional to increase in peak current, spark energy, and pulse on-time that lead to transfer more energy to electrode. An improvement of peak current with spark energy increases TWR [54]. During machining, workpiece removal rate (WRR) and TWR were increased with the increasing discharge current. TWR is inversely proportional to pulse time settings, but WRR is directly proportional to pulse time setting. The related wear is reduced with increasing pulse time, but slightly increases in related wear with increasing current [55]. From the comparative study of machining characteristic using different shapes of current impulse, it was noted that the use of rectangular current impulse always results the most MRR and RWR due to maximum starting current and shortest current increasing time. The trapezoidal current impulse with small initial current can decrease RWR but MRR is low due to small energy density. Non-trapezoidal pulse form is preferred for machining of high-melting-point material like tungsten carbide [56].

2.1.3 Surface quality

2.1.3.1 Surface quality analysis

The surface morphology is associated with various surface characteristics such as microhardness profile, surface roughness, residual stress geometric, crack density, white layer, crack density, etc. The surface morphology of a machined surface is becoming progressively more important to fulfilling the rising anxiety of complicated component performance, durability, and reliability. It plays an important role in industry and manufacturing sector in the inspection of product geometry, roughness, and dimensional accuracy. The surface integrity element measurement is a time-consuming process with the use of precious apparatus such as microhardness tester, XRD, SEM, and surface roughness tester. Surface roughness is a significant factor used to assess EDMed surface quality. In order to determine the effect of EDM parameters to account for SR in specimen, the surface profile on the machined samples were calculated using various equipment, namely, surface roughness tester, atomic force microscopy (AFM), 3D profiler, etc.

The average surface roughness (R_{a}) of the workpiece was measured from the AFM surface topographic data according to the following equation:

$$R_a = \frac{1}{MN}\sum_{i=1}^{M}\sum_{i=1}^{N}\left|Z\left(x_i, y_j\right)\right|. \tag{3}$$

Regression analysis was used to show the relation between various process parameters:

$$R_a = 21.0\left(I_p\right)^{0.33}(\tau_{\mathrm{on}})^{1.37}, \tag{4}$$

where $I_{P \text{ and } \tau_{\mathrm{on}}}$ denote pulse current and pulse-on duration [57], respectively.

It was also noticed that MRR and gap distance increases with increase in the discharge energy because of improvement of discharge power. The discharge energy is formulated as the following:

$$\text{EDM is discharge energy}: \; E_e = U_e.I_e.t_i \tag{5}$$

where U_e is the discharge voltage, I_e is the discharge current, and t_i is the pulse duration.

The rise in both discharge power and discharge duration leads to increase in SR. The more value of discharge energy increases recast layer thickness [58]. During EDM machining of steel, it was found that SR enhances with increase in the discharge duration as emission of high discharge energy and enlargement of the discharge channel [59]. During machining, the machined surface of specimen reveals coarse and spongy surface along with melting drops and craters that collapse the plasma columns. Simultaneously, crater's depth is increased as volume of the material removal increases due to more heat flow to specimen in machining. The combined form of recast sublayers as well as melted sublayers with dendritic structure form white layer thickness measured (WLT) in micrometers [60]. The crack density and depth of crack in the recast layer increase with increase in machining pulse energy [61]. During machining, the new configuration of pulse generator shows different shapes of pulse current such as sinusoidal or triangular shape. This new generator was applied for both positive and negative polarity and it established the improvement of machining efficiency. In bipolar mode, SR slightly increases and wear decreases as compared to unipolar mode due to redeposition of materials on electrode surface [62]. In machining of both MDN 250 and MDN 300 steel with positive polarity, lesser amount of material was liberated from the electrode due to less exposure of the electrode than specimen. The negative tool polarity confirmed more SR than the positive tool polarity because of the presence of heavy mass and energy-assisted positive ions in the discharge channel. Hence, the Si–C chemical bond could be simply fractured with positive ions that leads to stable electrical discharge [63]. The hole-drilling-induced stress was more sensitive to pulse current and pulse duration. The relative stability coefficient of the discharge duty duration reduces the enlargement of recast layer thickness and hole-drilling-induced stress. But this value remained larger than 0.99. Consequently, the hole-drilling-induced stress decreases because of improved pulse-off duration to particular limit; thereafter it is not affected with pulse-off duration [64]. The effect of deposition of carbon particle on the white layer of machined surface comes from both dielectric fluid and electrode in EDM. The carbon from electrode was more efficient for creation of austenite phase in white layer using deionized water as dielectric fluid. The surface residual stress on EDMed surface improves with increase in the nonhomogeneities in white layer [65]. It was also observed that high stress concentration on the white layer was due to presence of high Cr content [66].

The MRR is directly proportional to current, but it is inversely proportional to pulse duration due to reduction of spark efficiency that results in deposition of carbon obtained from breakdown of dielectric. The recast layer thickness is directly proportional to spark energy. But pulse on-time variation had better effect on recast layer thickness than current [67]. When morphology and elemental distribution on the cross section of the modified specimen is analyzed, the defects on the machined surface due to thermal stress are observed. It was also noted that Si layer deposition on the alloyed layer increase with increase in discharge resulting in increase of thickness of alloyed layer [68]. An average white layer thickness (AWLT) had better effect on spatial parameter (S_{ds}), whereas current had more influence on crater dimension than pulse on-time. An empirical nonlinear regression analysis of these data yielded AWLT:

$$\mathrm{AWLT} = 148.5(I)^{0.4}\cdot(t)^{0.25}. \tag{6}$$

AWLT is the average white layer thickness (μm), I is the pulse current (A), and t is the pulse on-time (μs). The thickness of the white layer relies on a single spark which is uniform in nature [69].

An actual spark off-time is linearly increased with effective erosion area as its duration is more than pulse off-time. Small erosion area affects the range of the discharge channel, erosion area, and the pulse frequency. For this reason, small erosion area machining requiring pulse off-time can be noticed in equation (7):

$$T_{\text{off}} = \frac{L\cdot A_e\cdot t_p}{C\cdot\pi\cdot r^2\cdot e}\cdot(1+\Phi_{\mathrm{OL}}), \tag{7}$$

where Φ_{OL} is the percentage of open-circuit or no-load pulses. L denotes the overlap coefficient with closer value to unity; C indicates multiple-channel discharges effect, and t_p is the pulse period. The actual off-time maintains nonlinear relation with normal surface removal rate. A large surface of the specimen allows a high discharge current because of long actual off-time [70].

2.1.3.2 *Method of improving surface quality*

The multistage planetary EDM was preferred due to its low machining time and electrode cost in finishing operation. In this EDM, suitable surface finish could be achieved with modifying working time and machining time. It also estimated thermally induced deformations in both electrodes with experimentation to measure temperature [71]. Temperature in the specimen spark cavity decreases as the distance from the spark cavity surface increases. Long spark-on time with high peak-ampere machining normally requires finish-machining operations to improve the spark cavity surface metallurgy. When very high spark energy machining operations are performed, up to 0.76 mm of the rough surface may need to be removed by finish machining in order to provide an acceptable surface metallurgy [5]. The relationship is established between SR value obtained from EDM experiments of cold work tool steel using the genetic expression programming method and mathematical model. It was concluded that the powder material used in machining process generate smaller SR whereas similar SR was obtained using tungsten and graphite electrode. The genetic expression programme revealed close roughness value nearly equal to actual roughness value [72]. Similarly, the higher values of pulse current and pulse time increase SR. The low current, pulse time, and high pause time provide good surface finish. It was also found that sample surface finish decreases because of wear rate on electrode. On the contrary, SR of machined specimen increases when surface quality of electrode decreases due to pulse current density [73]. During machining of both B_4C and WC-Co surface, it was observed that SR was inversely proportional to voltage, whereas EW was directly proportional to pulse duration. The higher value of material removal rate was associated with increase in both intensity and pulse duration [74].

The EDM used silicon powder and good flushing flow rate improves surface morphology. For a particular condition, the best surface topography was achieved while a powder concentration is in the range of 2–3 g/L. It was also observed that better effect of silicon powder showed decrease in crater dimension, recast layer thickness, and SR. Furthermore, the controlled dielectric flow rate minimized the SR to achieve an improved surface morphology [75]. The use of liquid nitrogen in EDM of titanium alloy showed the decrease of EW and SR of titanium alloy. It was also observed that the liquid nitrogen improves good electrical and thermal conductivity of copper and reduces EW of copper [76]. The improvement of EDM process is achieved by establishing the relation among process parameters with surface cracks. The SR and WLT increase with increases of pulse current and pulse-on duration. It was also found that crack observation on the H13 surface is less than D2 die steel surface [77]. A combined EDM and polishing electromechanical process was used with electrorheological fluid and Al_2O_3 abrasive particle for machining. It was concluded that improvement of SR could be achieved using aluminum powder with ER fluid [78]. During the machining of titanium using urea into dielectric fluid, the MRR and EW rate increase with rise in peak current but decrease with increase in pulse duration due to large plasma channel. The SR deteriorates due to higher value of peak current. The modified titanium metal revealed the improvement of friction and wear properties [79]. The state of tensile and fatigue properties of machined surface for different microstructure of Ti–6Al–4V alloy were improved for the fatigue endurance applicable in orthopedic purpose. During EDM process, various microstructures such as equiaxed, bimodal, and coarse lamellar were prepared from Ti–6Al–4V alloy. In this work, specimen surface composition could be improved using a high peak current [80]. While comparing the performance of three electrodes, namely, copper, graphite, and tungsten in EDM process, it was concluded that copper electrode shows the best surface finish, whereas tungsten carbide shows poorest surface finish. In addition, copper provides the highest axial error due to greater tool wear, whereas graphite provides least value of axial error due to its highest melting point. The graphite also provides least value of diameter error, but copper provides the greatest value of diameter error for all conditions [81]. During the EDM of DIN 1.2080 and DIN 1.2379 using two special graphite such as Dura graphite 11 and Poco graphite EDMC-3, it was noticed that SR was quite similar in both steel. The SR shows linear relation with the pulse current due to more quantity of molten and suspended particle in interelectrode gap. The unfavorable erosion quality of Dura graphite promotes SR upon DIN1.2080 specimen for all machining conditions. It was also noticed that lowering the pulse current results in the elimination of microcracks formation because of high thermal gradient below the melting zone. The residual stresses increase with soft machining due to higher pulse duration using Poco graphite electrode [82]. During the machining of steel using urea with deionized water, it was observed that machined surface is harder due to the presence of nitrogen concentration [83]. On the other hand, during EDM of Inconel 718 using copper electrode, it was observed that MRR improves because of rise in the peak current up to a certain point as increase in spark energy takes place but then it starts decreasing due to high ignition delay, which occurs due to high pulse interval in each cycle. Copper electrode revealed less EWR due to longer pulse duration which results more carbon deposited on the copper electrode. But in this case, pulse duration was linearly increasing with SR [84].

When the EDM machining is performed with optimized parameter in interelectrode gap, it was investigated that MRR is directly proportional to long pulse on-time because of more expansion of plasma channel. The surface finish is better with the application of low pulse on-time due to formation of small particle and crater depth. It also indicated that gap size is significantly affected by pulse on-time and little bit affected by average machining voltage which is due to the linear relationship between MRR and gap size [85].

Electrodischarge machining in comparison to electro discharge sawing (EDS) revealed that EDS had higher erosion rate than EDM due to rough erode surface [86]. While comparing the fracture strength of both machined and unmachined WC-Co cemented carbide in machining, the increase in discharge energy on machined surface generates rougher surface which consists of debris, crater, and microcracks due to more quantity of molten and floating metal suspended in discharge gap. The crater and microcracks were observed on the machined surface because of greater thermal stress that results in the reduction of the fracture strength of specimen [87]. Increase in discharge energy and discharge duration (pulse duration) increases MRR and gas bubbles in the machining zone. Consequently, increase in discharge power and discharge duration results in the large gap distance that maintain stability of EDM process. Higher is the value of discharge power along with discharge duration, rise is in the SR value due to formation of more crater on machined surface. The increase of the discharge energy also increases the recast layer thickness but layer thickness is more influenced by discharge duration [58]. From the viewpoint of low EW and discharge current during machining of nickel-based alloy MAR-M247, longer pulse duration and higher open-circuit voltage should be applied to improve the surface quality and cub-surface damage [88]. When comparative study of B_4C and WC-Co conductive ceramics were made, it was observed that voltage is inversely related to SR. The B_4C showed more the recast material formation than that of WC-Co due to difficulty of the material erosion to dielectric fluid because of its high melting and vaporization point. The electrode wear is inversely proportional to pulse on-time due to low value of frequency, but it is directly proportional to voltage [89]. During machining of tool steel, it was pointed out that wire brushing and polishing are used to eliminate the crack network from machined surface. The polishing process is more preferable than wire brushing [90]. The wear resistance of the machined specimen can be improved under extreme pressure and temperature condition using WC powder compacted electrode [91]. A small and lightweight equipment using a developed synchronous converter had been introduced in EDM. This equipment could change the frequency, duty cycle, and polarity of the discharge current employed at the EDM power supply. The surface finish is finer in case of the lighter frequency biopolar operating mode [92]. The abrasive fluid machine improves SR and shape precision of microholes. An abrasive fluid machine procedure was accepted for finishing of the microhole manufactured by EDM on SUS 304 plate and titanium alloy. All EDM parameters showed less effect for decreasing the difference between the dimensions of the entrance and the exit [93]. During EDM of gamma titanium aluminide with fine graphite, it was reported that SR had no effect with pulse interval time. The WLT increases little bit with increase in pulse interval time. The duty factor was independent of SR, but average WLT slightly decreased with increase of duty cycle which was mainly due to less energy density in interelectrode gap [94].

During the machining of Inconel 825 with die sinking EDM, it was noticed that minimum SR was obtained by optimizing process variables such as pulse on-time and pulse off-time and peak current. But current shows the most effectiveness on the SR in comparison to pulse on-time and pulse off-time [95]. During the machining of steel using deionized water as dielectric, it was found that SR can be reduced with varying process variable like pulse on-time, peak current, gap voltage, and duty cycle. But peak current and pulse on-time have more impact on SR reduction in comparison to gap voltage and duty cycle [96].

3 Modeling and optimization of performance parameter

Modeling used in EDM provides better clarification of complex process. In 1979, Jeswani used the modeling with dimensional analysis for calculating the TW. Furthermore, numerous methods were used to predict the machining performance of EDM process.

3.1 Modeling and optimization of MRR

A thermal model capable of simulating discharge superposition and machining surface is used to explain the energy transfer to the specimen, the discharge channel, and MRR. The validated experimental result with simulated result shows good agreement of MRR and SR with less error [97]. A thermal model is used to identify the MRR along with the average SR. The model predicted the increase of the discharge current, the arc voltage, or the spark duration that results in higher MRR and coarse sample surfaces. On the contrary, the idle time is inversely proportional to the MRR with further improvement of achieving a little bit superior SR [98]. An axisymmetric thermophysical model associated with finite element method was used for die sinking EDM based on Gaussian distribution of heat source and spark radius equation. It predicted crater cavity form and the MRR. The computed MRR ($\mathrm{mm}^3/\mathrm{min}$) is

$$\mathrm{MRR}\left(\frac{\mathrm{mm}^3}{\mathrm{min}}\right) = \frac{60 \times C_{VT}}{t_{\mathrm{on}} \times t_{\mathrm{off}}}, \tag{8}$$

where C_{VT} is the material removed per discharge pulse, t_{on} is the discharge duration and t_{off} is the discharge off-time. The results predicted by their model were validated with the experimental data [99]. From the viewpoint of comparative study of various EDM models, namely, Snoeys, Van Dijck, Beck, Jilani, and DiBitonto, it was reported that DiBitonto model showed energy collection from 0.33 to 952 mJ and produced the closeness of 1.2–46.1 in terms of MRR. This MRR ratio is in good agreement with experimental data as compared to other models. The discussed disk heat source model could be used by improving the heat flux and energy fraction [100]. A predicted linear regression model is used to describe the interaction of hardness, MRR, and SR of alloyed steel. This linear regression model confirmed that MRR and the sample SR are reliant on sample hardness. The MRR was guessed with an average error of 1.06% and sample SR values with an average error of 0.4% [101]. During the effect of input process parameters in the machining of two-electrode 316L as specimen and copper-impregnated graphite as tool, it was noticed that a mathematical modeling was used for resulting parameters, namely MRR, EW, SR, and dimensional accuracy which showed the result with less than 15% error. Therefore, the developed model is suitable for all response variable and dimensional accuracy [102]. During the machining of Inconel 718 alloy, a proposed model showed the increase of current and duty cycle as more energetic pulses increases MRR. The electrode wear is nonlinearly related with the pulse time resulting in decrease in spark energy. The SR is directly proportional to both current intensity and pulse time as more energetic pulse creates larger and deeper crater in machined surface [103]. With the use of a second-order mathematical model, the MRR can be analyzed using response surface methodology based on the experimental result. The MRR showed linear relation with pulse current and pulse on-time due to higher spark energy, but it is inversely related to pulse off-time [104]. When process parameters are optimized in EDM of carbon–carbon composites using experiments based on Taguchi method, the parameters at worst value reduce the EW rate while parameters set at their optimal value improves MRR [105]. The combined Taguchi dynamic approach and proposed ideal function is used to develop a suitable high-speed EDM method along with geometrical machining precision and accuracy optimization. It was also found that there is no significant effect of powder-related factors of the process design in process robustness and machining accuracy [106].

The layer removal method is used in thin parallelepiped test specimen to find out the residual stress profile of machined DIN 1.2738 steel. A considerable amount of residual stress and cracking on machined sample for long pulse duration was found. In addition, the use of model based on the Gauss distribution represents the modification in curvature by means of removal depth [107]. Classification of major EDM research areas is given in Figure 1.

3.2 Modeling and optimization of tool wear rate

An inverse form of suitable tool shape is used to achieve the desired final sample shape using developed simulation model in die-sinking EDM. This developed simulation considered various factors, namely, tool electrode wear, gap width distribution, curvature of the tool electrode surface, and debris particle concentration in EDM [108]. A combined neuro-fuzzy system and neural network model is developed to establish a relation among various process parameters: MRR, TWR, and overcut increase with increase in pulse current as well as pulse on-time [109]. A numerical model for electrical-assisted embossing process is used and compared it with experimental analysis. From this comparison, it was concluded that both the

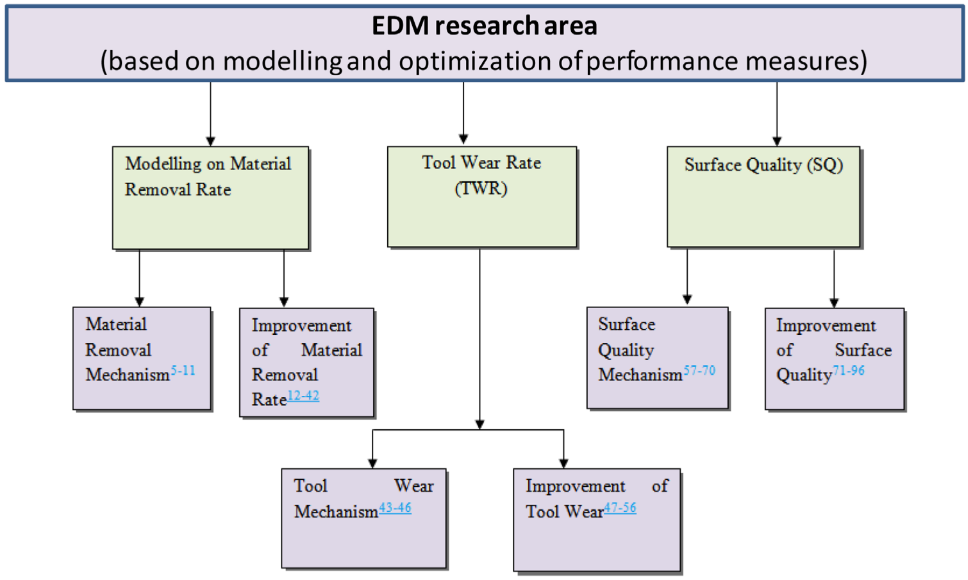

Fig. 1. Classification of major EDM research areas.

numerical simulation and experimentation revealed the increase in the depth of microchannel of machined samples. It also found that the improvement of formability occurs due to decrease in flow stress of specimen [110].

3.3 Modeling and optimization of surface quality

A mathematical modeling is used for selection of the optimal machining condition for finishing operation. An improvement of pulse on-time increases SR and it decreases with pause time. Higher value of duty cycle provides poor SR of the specimen. Extremely low value of pulse time also offers small values of EW. In addition, MRR is directly proportional to intensity and duty cycle [111]. A combined hybrid artificial neural network (ANN) and genetic algorithm (GA) methods are used for optimization of EDM machining. This model considered varying peak current and voltage and its effect on SR [112]. A mathematical model was proposed to investigate process parameters in the EDM machining of aluminum-based ceramic. The MRR increases with increase of discharge current, duty factor, and open discharge voltage. It was also noticed that EWR shows nonlinear relation with discharge current, whereas it maintains linear relation with duty factor along with open discharge voltage. The SR is directly proportional to both discharge current and open discharge voltage, but is inversely proportional to duty factor [113].

A model analyzed the rapidly resolidified layer of spheroidal graphite (SG) cast iron based on response surface methodology. The use of graphite particle in machining results in the reduction of layer thickness and increase in diameter of the graphite particle. The ridges density increases with increase in the quantity and area fraction of graphite particle [114]. A mathematical model is used to minimize surface defects. The SR increases with increase in peak current. The improvement of WLT was observed with rise in the peak current due to improper flushing of molten metal. In addition, the effect of surface crack density on pulse current was nonlinear in nature for a certain value of pulse-on duration and WLT. The AWLT increases with pulse-on duration that results in more stress [115]. The developed geometric model is beneficial for the attached linear motor-sinking EDM. For a particular condition, the single spark erosion for linear motor is equipped with EDM. The model simulated the influence of discharge duration and peak current on the average SR [116]. An inversion model showed that SR increases with the peak current level: the increase in current and pulse on-time in positive charged electrodes, EWR decreases, and the increase in pulse on-time increases the MRR [117]. The effect of pulse current had significantly linear relation with the EDM surface texture and square surface parameters [118]. A fabricated powder metallurgy compact tool using tungsten and copper powder is used to facilitate the improvement of SR on plain carbon steel. The L-16 orthogonal array as Taguchi method and analysis of variance (ANOVA) can be implemented for the study of relevant parameters. The simulated result obtained from the networks was in good agreement with experimental data [119]. During the machining using Gray–Taguchi method, the current showed dominant effects on the SR as compared to other parameters [120]. The empirical relation while machining of steel with Al–Cu–Si–TiC powder compact electrode showed the effect among the input response and output response parameters.

The SR was greatly affected by Al–Cu–Si–TiC powder electrode [121]. A model can be used to express EW and WLT using response surface methodology. The EW and WLT linearly rise, especially when the pulse current increases [122]. A neural network model was used to predict surface change in machining with tungsten–copper powder metallurgy-sintered electrodes. The material transfer rate and layer thickness not only increases with the rise in pulse on-time but also decreases with the increase in compaction pressure. Overall, the comparison in both the artificial neural network data and experimental data showed good agreement in the results [123]. The dominant effect of thermal spalling mechanism was considered in machining TiB_2BY using a model based on the expansion of plasma channel and long pulse period. The model could predict flake thickness on surface. This model could be used for die-sinking EDM and wire-cutting machine [124].

3.4 Mathematical analysis/algorithm for the machining performances optimization in EDM

Kishan et al. developed mathematical model to optimize the input parameters for each tool used for machining by design of experiments. Metal removal rate (MR) is calculated from weight difference of workpiece before and after the performance test. $\mathrm{MR} = (W_i - W_f) \cdot 1000/d \cdot t$, where W_i = initial weight of workpiece in grams, W_f = final weight of workpiece in grams, t = period of trials in minutes, d = density of workpiece in g/cm^3 [125]. Maradia et al. used stochastic optimization algorithm to optimize EDM drilling process. The robustness of the algorithm is evaluated for diverse EDM drilling process disturbances, such as electrode length and electrode shape. The performance of the optimization algorithm is further evaluated in terms of effect of initial parameters and number of iterations required to converge to the optimal parameter values, to achieve highest material removal rate (MRR). It is found that the optimization algorithm is able to turn up at the optimal values after ∼40 iterations, where the achieved MRR is at least 10% higher than the MRR obtained by using the high-speed strategy from the standard machine technology [126].

Furthermore, Abdolahi et al. developed a model that utilizes "nondimensional process evaluating function" (NPEF) and predicts the optimum parameters concerning the desired machining situation that finally identifies a set of mathematical equations to compute optimum values for machining. NPEF involves four scaled terms, summarized mathematically together to cover the wide range of machining parameters with different units in an equation. This is derived from a primary concept of a normalized equation, which generates dimensionless normalized terms by dividing the parameters by current mean value. Then, the last idea is developed to be independent of the running machining process, and NPEF function is produced, as presented in following equation. NPEF is introduced as the mathematical basis to be implemented in the further steps:

$$\mathrm{NPEF} = \alpha P_a + \beta Q_b + \gamma R_c + \lambda S_d,$$

where P is the dimensionless parameter of length, dependence of electrode wear, and workpiece thickness; Q is the time involving the machining time and the frequency of electrode's forehead motion; R is the surface roughness and its quality; S is the representative of percentages of successful discharges, open circuits, and short circuits [127].

In another work related to optimization of process parameters, Raju et al. used Gray relational analysis to find a unique optimal parameter setting conditions for micro-electrical discharge machining (micro-EDM) drilling process of Inconel 600 alloy. For this, the five effective process parameters, namely, voltage, capacitance, EDM feed rate, pulse on-time, and pulse off-time, are varied and microholes were drilled using tungsten carbide tool. The material removal rate, taper angle, overcut, and diametric variance at the entry and exit of a microhole were the considered performance characteristics. Analysis of variance (ANOVA) was performed to realize the effects, contributions, and consequence of the process parameters. Capacitance is observed the most influencing parameter followed by the voltage and EDM feed rate controls the taper angle. From the confirmatory test results, it is revealed that optimized parameter setting gives better machining performance characteristics [128].

In another work, quadratic regression models for the individual responses and multiobjective particle swarm optimization (MOPSO) algorithm were implemented by Dhupal et al. [129] to find the optimal process parameter settings. MOPSO algorithm presents valuable information for governing the machining parameters to enhance accuracy of the electrical discharge machined parts. Nagaraju et al. used fuzzy method coupled with Taguchi to optimize multiple responses of EDM. The effect of machining parameters, i.e., discharge current, pulse on-time, discharge voltage, and interelectrode gap (IEG) on MRR, tool wear rate, and surface roughness (R_a) in EDM were investigated. The multiple responses were converted into a single characteristic index by using fuzzy logic known as Multi-Performance Characteristic Index (MPCI). Finally, MPCIs were optimized by using Taguchi method. The performance characteristics such as MRR, R_a, and TWR were improved by using the current analysis [130].

Shao et al. demonstrated comprehensive electrothermal model of μ-EDM to simulate the crater formation process. This model incorporates realistic machining conditions such as Gaussian-distributed heat flux, temperature-dependent thermal properties, and expanding plasma radius. The heat transfer equation and experimental measurements of a generated crater dimensions are used to determine the energy distribution fraction to the electrodes, a critical parameter of the μ-EDM modeling [131].

Parsana et al. studied parametric multiobjective optimization of EDM on Mg–RE–Zn–Zr alloy using the novel metaheuristic algorithm – passing vehicle search (PVS). The input parameters considered were peak current, pulse on-time, and pulse off-time. Response surface method (RSM) is realized through the Box–Behnken design to formulate a mathematical model for MRR, TWR, and roundness of holes. EDM machining was effectively conducted on Mg–RE alloy and the experimental results were used to develop a mathematical model which was successfully analyzed using modified multivariate PVS algorithm. Box–Behnken design proved competent in mathematical modeling of MRR, TWR, and roundedness of holes by minimizing number of trials. The statistical analysis based on ANOVA (p-value < 0.01) results led to end that for EDM process, on average, pulse off-time is slightest influencing parameter while pulse on-time and peak current are dominating control parameters for objectives evaluated in the study [132].

Prakash et al. used HA (hydroxyapatite) powder-mixed EDM process to deposit HA over biodegradable Mg–Zn–Mn alloy. The process parameters have been optimized using multiobjective particle swarm optimization (MO-PSO) technique to determine the optimal levels of concentration of HA powder, peak current, pulse on-time, and pulse off-time [133].

Ramanan et al. evaluated the quality of the machined samples by the measurement of material removal rate and surface roughness. Results are utilized to develop the Gray-fuzzy model. From this technique, the optimum combinations of process parameters are obtained and corresponding values of maximum MRR and minimum SR are found out [134].

Aharwal et al. optimized the machining parameters on EDM using AlSiC as workpiece and pure copper as electrode. Machining parameters investigated in this work are MRR and SR. Control parameters used are discharge voltage (v), discharge current (I_{p}), pulse duty factor (T_{au}), and pulse on-time (T_{on}) [135].

4 Summary of the previous review papers based on the EDM-based research

Table 1 summarizes the recent review papers published in EDM-based work.

5 EDM for new applications

In order to meet the current technological requirement, the first activity performed is the modification of existing conventional electrodischarge machining system to micro-EDM. EDM has now been translated into various modules, viz., wire EDM, dry EDM, ultrasonic-assisted EDM, etc. Modern manufacturing industries, viz., micro/nano tools manufacture, aerospace, and robotics industries, have lots of difficulty to machine and work with advanced materials like superalloys, metal–matrix composites, cemented carbide, etc. To overcome this difficulty, EDM and its modified versions, among many advanced manufacturing processes, is well preferred in recent industrial applications. To achieve the dimensional accuracy and avoid manual errors, EDMs are equipped with CNC nowadays. As one of the modified EDM versions, wire-EDM is being utilized to cut intricate shapes but practical limitations, viz., handling of larger parts, nonavailability of smaller wire size, etc. hinder its application to fewer cases. Nowadays, EDM is being combined with other nontraditional processes to explore a newer applications called hybrid machining processes (HMPs) in which the demerits of EDMs have been effectively overcome. Some recent extensive applications of EDM in modern manufacturing industries are discussed in the following sections.

5.1 Production of nanoparticles

Nickel nanoparticles are produced by micro-EDM process with optimization of different process parameters fit to nanoapplications. Deionized water is used as a dielectric medium in production process of nickel nanoparticles in micro-EDM. Polyvinyl alcohol is used as a stabilizing agent in this process. Different characterization techniques such as X-ray diffraction (XRD), scanning electron microscope (SEM), and UV-vis spectroscopy are used to study structural and functional properties of such nanoparticles. In micro-EDM process, the mean crystal size of the nanoparticles of nickel metal can be obtained on the order of 15–20 nm with a pulse on-time varying from 2 to 0.3 µs. The crystal size can be further decreased by decreasing the pulse on-time. Viscosity measurement is useful to predict the dispersion stability of nickel nanofluid. Pulse duration plays an important role in decreasing/increasing the dynamic viscosity of the nanofluid. As per the analysis using Fourier transform infrared (FTIR) method, the use of deionized water in this process produces pure and monolithic nickel particles [155]. Figure 2 shows the micro-EDM setup for production of nickel nanoparticles, which consists of different components such as (i) transistor-type pulse generator, (ii) stepper motor-controlled tool motion (Z-motion), (iii) machining tank filled with DI water, and (iv) work table (for precise movement of X- and Y-axes). Transistor-type pulse generator was used to get a higher metal removal rate with uniformly discharging phenomenon. The capacity of the power source is designed to generate 150 V output pulses across a resistive load at a pulse frequency of 100 Hz–10 kHz, which can be programmed through a microcontroller [155].

5.2 Machining of metal matrix composites using W-EDM

Wire electrical discharge machining (WEDM) is one of the popular noncontact techniques of machining process. In earlier days, this process is normally used to produce mere tool to complex die-making process. To meet the up-to-date requirements, WEDM process is the more preferable process used for machining of materials starting from conventional materials to nascent materials such as metal–matrix composites and ceramic composites, which have vast applications in automobile, military, aircraft, railway sectors, aerospace, microsystems industries, agriculture farm machinery, etc. [156].

Metal–matrix composites are considered as advanced material having different properties such as it is very lightweight and has good wear resistance, high specific strength, low thermal expansion coefficient, and low density. Though these materials can be machined by nonconventional methods such as water jet and laser cutting, to name but a few, these processes are restricted to linear cutting only. Wire electrical discharge machining (WEDM) can be used for generating complex shapes with high precision for metal–matrix composites. In case of conventional machining process, cutting metal–matrix composites causes severe tool wear due to greater hardness and the existence of abrasive reinforcement particles [156].

5.3 Hybrid machining process using EDM

The combination of EDM with other techniques evolves a new process called hybrid machining process. The effective implementation of the technique either ultrasonic

Table 1. The work of recently published review articles based on EDM in past 5 years.

S. No.	Authors	Title of the paper	Aim of the paper	Year	Reference
1	Manjaiah, M., Narendranath, S., Basavarajappa, S.	A review on machining of titanium based alloys using EDM and WEDM	The aim of this review is to present the consolidated information about the contributions of various researchers on the application of EDM and WEDM on titanium materials	2014	[136]
2	Maher, I., Sarhan, A.A.D., Hamdi, M.	Review of improvements in wire electrode properties for longer working time and utilization in wire EDM machining	This paper focuses on the evolution of EDM wire electrode technologies from using copper to the widely employed brass wire electrodes and from brass wire electrodes to the latest coated wire electrodes	2015	[137]
3	Bajaj, R., Tiwari, A. K., Dixit, A.R.	Current trends in electric discharge machining using micro and nano powder materials: a review	This paper presents a summary of some important research work done on PMEDM by mixing micro- and nanosized particle in the dielectric fluid of EDM	2015	[138]
4	Chakraborty, S., Dey, V., Ghosh, S.K.	A review on the use of dielectric fluids and their effects in electrical discharge machining characteristics	This paper presents a literature survey on the use of dielectric fluids and also their effects in electrical discharge machining characteristics	2015	[139]
5	Muthuramalingam, T., Mohan, B.	A review on influence of electrical process parameters in EDM process	This study discusses an overview of the EDM process, influence of process parameters such as input electrical variables, pulse shape, and discharge energy on performance measures such as material removal rate, surface roughness, and electrode wear rate	2015	[140]
6	Mohal, S., Kumar, H., Kansal, S.K.	Nano-finishing of materials by powder mixed electric discharge machining (PMEDM): a review	This paper presents a review of the ongoing research and development in PMEDM, NPMEDM followed by an in-depth discussion on high material removal rate (MRR), low tool wear rate (TWR), low surface roughness (SR), surface modification of workpiece, optimization of process parameters, and process modeling and simulation	2015	[141]
7	Santarao, K., Prasad, C.L.V.R.S. V., Gurugubelli, S.N.	Influence of nano and micro powders in electric discharge machining: a review	This paper presents the effect of nano- and micropowders blended in dielectric medium used in EDM and their influence on MRR, SR, TWR, and white layer thickness (WLT) with the variation of electrical (pulse-on time and peak current), nonelectrical (flushing), powder (type, size, and concentration), and electrode parameters	2016	[142]

Table 1. (continued).

S. No.	Authors	Title of the paper	Aim of the paper	Year	Reference
8	Liu, Q., Zhang, Q., Zhang, M., Zhang, J.	Review of size effects in micro electrical discharge machining	This paper contains a comprehensive review of size effects in traditional micromachining and characteristics specific to micro-EDM compared to macro-EDM techniques	2016	[143]
9	Shabgard, M.R., Gholipoor, A., Baseri, H.	A review on recent developments in machining methods based on electrical discharge phenomena	This paper reviews the current research trends in EDM process containing dry EDM, near-dry EDM, magnetic field-assisted EDM, ultrasonic vibrations-assisted EDM, and powder-mixed EDM processes which were developed in order to overcome the limitations of EDM process	2016	[144]
10	Banu, A., Ali, Mohammad Y.	Electrical discharge machining (EDM): a review	This paper provides an important review on different types of EDM operations. A brief discussion is also performed on the machining responses and mathematical modeling	2016	[145]
11	Gangil M., Pradhan, M.K	Modeling and optimization of electrical discharge machining process using RSM: a review	The main focus is on the optimization aspects of various parameters of the EDM processes using RSM & hence only such research works are included in this work.	2017	[146]
12	Abdul et al.	A review of additive mixed- electric discharge machining: current status and future perspectives for surface modification of biomedical implants	This paper reports and summarizes the current advancement of AM-EDM as a potential tool for orthopedic and dental implant fabrication	2017	[147]
13	Hourmand, M., Sarhan, A.A.D., Mohd Sayuti	Micro-electrode fabrication processes for micro-EDM drilling and milling: a state-of-the-art review	This paper presents a state-of-the-art review of micro-EDM process as well as the various kinds of microelectrode and workpiece materials and dielectrics that have been used by previous researchers	2017	[148]
14	Meshram, D. B., Puri, Y. M.	Review of research work in die-sinking EDM for machining curved hole	This review paper explains the mechanisms and methods adopted for developing the curved hole machining	2017	[149]
15	Aidil, A.R.M., Minhat, M., Hussein, N.I.S.	Current research trends in wire electrical discharge machining (WEDM): a review	This paper reviews the experimental results on performance evaluation of machining parameters that affected machining performance which would reflect the machining factors and responses	2018	[150]

Table 1. (continued).

S. No.	Authors	Title of the paper	Aim of the paper	Year	Reference
16	Selvarajana, L., Manoharb, M., Amos Robert Jayachandran, J., Selvakumare, P.M.P.	A Review on Less Tool Wear Rate and Improving Surface Quality of Conductive Ceramic Composites by Spark EDM A Review on Less Tool Wear Rate and Improving Surface Quality of Conductive Ceramic Composites by Spark EDM A review on less tool wear rate and improving surface quality of conductive ceramic composites by spark EDM	In this paper authors have reviewed the research work carried out in the development of EDM in the past decades for the improvement of machining characteristics such as surface roughness and tool wear ratio	2018	[151]
17	Patel, J.B., Darji, R. S., Dalai, M.K.	Powder mixed EDM for improvement of MRR and surface finish: a review	From the review, it can be understood that the optimization of input parameters of PMEDM like pulse on-time, pulse off-time, servo voltage, peak current, slurry concentration, flushing pressure can improve the characteristics	2018	[152]
18	Maity, K.P., Choubey, M.	A review on vibration-assisted EDM, micro-EDM and WEDM	This paper reviews the research work carried out by the researchers on vibration-assisted EDM, micro-EDM, and wire EDM	2018	[153]
19	Kumar, V., Beri, N., Kumar, A.	Electric discharge machining of titanium and alloys for biomedical implant applications: a review	This review paper clearly exhibits the detailed study of parameters that critically influence the machinability and the optimal combination levels of machining parameters for MRR, TWR, SR, and WR	2018	[154]

This review covers the description of performance measures for electro-discharge machining, review on modeling and optimization of performance parameters, detailed mathematical procedure used in various EDM analysis as well as current state-of-the-art work performed with description of newer applications of EDM.

vibration-assisted or laser beam-assisted EDM is widely used. In case of ultrasonic-assisted EDM (UAEDM), combining of EDM with ultrasonic vibrations is found to be one of the most effective shared hybrid machining processes with increased metal removal rate during machining of electrically conductive very hard materials [157].

Hybrid machining process which combines laser and micro-EDM processes for drilling microholes in complex engineering materials such as nickel–titanium (Ni–Ti)-based shape memory alloy (SMA) is an example of recent use of hybrid machining process technique [158]. Electro-discharge principle of machining has been coupled with electrolysis principle (as a result, hybrid process is known as electrochemical discharge machining process (ECDM)). Cao et al. utilized this hybrid process to fabricate three-dimensional microstructures in glass materials [159].

5.4 Magnetic field-assisted micro-EDM (MFMEDM)

The present machining scenario in micro-EDM, the removal of debris from workpiece, and tool have become

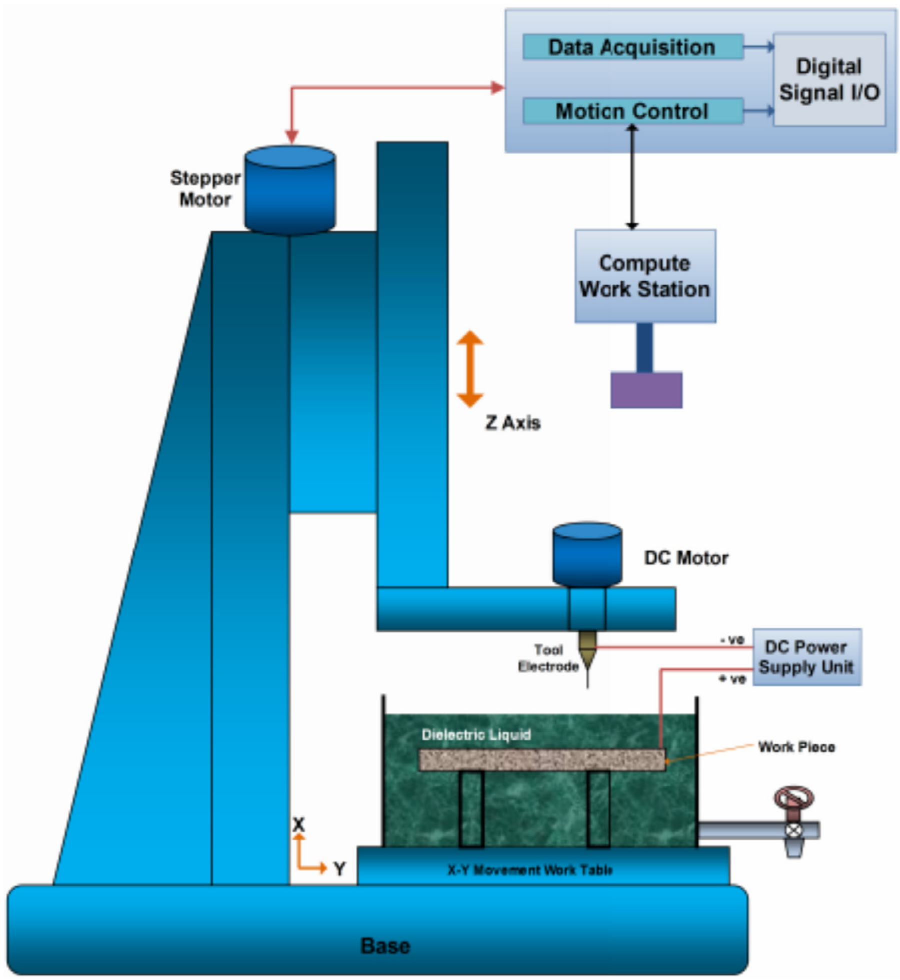

Fig. 2. Micro-EDM setup.

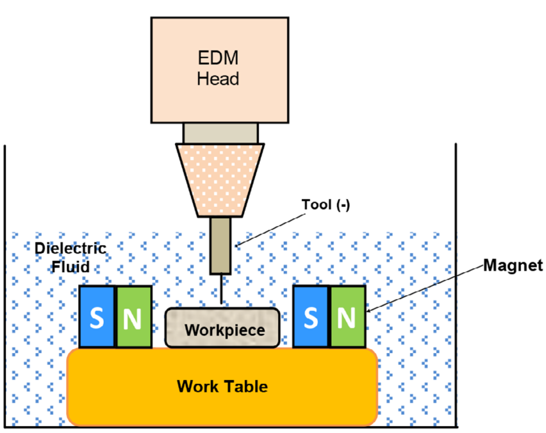

Fig. 3. Schematic diagram of MFMEDM (magnetic force-assisted micro-EDM).

a real challenge while performing micromachining. In micro-EDM process, the debris come out from workpiece and tool as melting process is solidified which affected the workpiece and the efficiency of machining process as well. Therefore, removal of debris is very important in order to obtain high-quality micromachining and better surface finish. Magnetic-field-assisted micro-EDM (MFMEDM) is one of newly emerging research techniques, in which debris are removed and gaps are cleaned by means of magnetic and centrifugal forces [160].

The general arrangements of magnetic force-assisted micro-EDM process is shown in Figure 3, in which magnetic field is produced by the magnets placed on both sides of the workpiece micro-EDM setup. The magnetic force created inside will help to remove quickly the unwanted material/debris coming out from workpiece during melting process as compared to normal micro-EDM. The resultant force by which unwanted material/debris are removed can be estimated as the vector addition of the magnetic force and centrifugal force.

5.5 Green EDM machining

EDM process uses hydrocarbon oil as a dielectric liquid. During sparking, very harmful vapors are generated from this dielectric liquid which is a serious issue of environmental disruption. The present research on EDM is focused on to overcome the pollution created by this harmful vapor

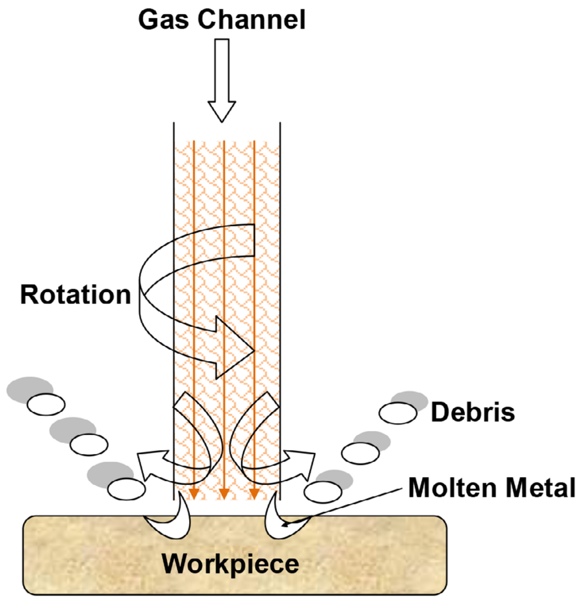

Fig. 4. Schematic diagram of DEDM.

generated during EDM machining process. The researcher suggested a new approach of EDM process, called dry-EDM (DEDM), near-dry EDM (NDEDM), and EDM in water, which is considered as an environment-friendly and an alternative of the oil EDM process referred to as a green EDM process [161].

As shown in Figure 4, high compressed gas or air is used in DEDM process. This compressed air or gas passes through a thin-walled tubular pipe; when compressed gas cools, the interelectrode gap relieved the debris from the machining zone. The procedure does not pose a health hazard since toxic fumes are not generated throughout machining. In addition, absence of mineral oil-based dielectrics drastically reduces fire hazards during the procedure. The aim of green manufacturing is to improve the efficiency of process and reduce the operating cost.

5.6 Multineedle brain implant

It is possible by the researchers to develop a multineedle using micro-EDM process which when used as a multiple-needle brain implant (Fig. 5) is inserted into an area of the patient's brain responsible for motor function. It is nearly impossible to maintain the dimension of the needles required for a uniform array formation in traditional machining techniques on a very hard machining material. Using micro-EDM technique, the implant of the size of a match head containing 100 sensors was made using an extremely hard material, namely, tungsten carbide [162].

5.7 Powder-mixed EDM (PMEDM)

Application of appropriate powder particles in EDM enhances the surface finish with higher metal removal rate as compared to traditional EDM process. A distinctive dielectric circulation system used in PMEDM is shown in Figure 6. This kind of system is particularly designed so that it can be placed in the working tank of an EDM setup. Normally powder particles are deposited at the bottom part of the dielectric reservoir which may be stagnated on workpiece. To avoid such settling, a stirrer or a micropump is provided in the setup. In order to remove the debris, a set of magnets is also provided [163].

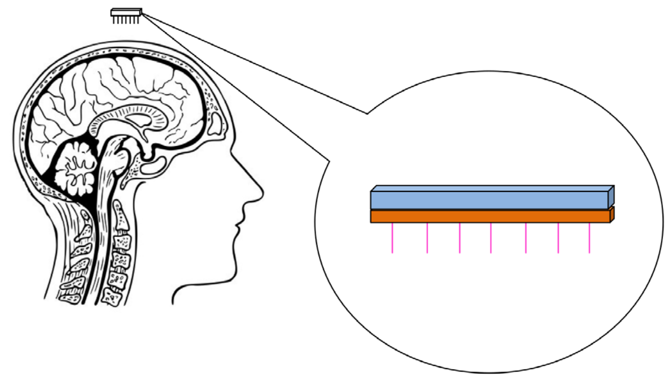

Fig. 5. Multineedle brain implant.

Since the inception of EDM usage in die-sinking applications, EDM has also been utilized for various micromachining applications. EDM concept has now been utilized for performing drilling (μ-EDM drilling), milling (μ-EDM milling), grinding (μ-EDM grinding), etc. Capabilities of EDM has been explored in producing microinjection moulds, optoelectronic components, stamping tools, fluidic structures, and many more. For large to micromachining, important amendment has been made in EDM in circuitry element. RC relaxation-type circuit has been transformed into RC single pulse discharge which has bestowed EDM the capability of producing single spark phenomenon. Overall micro-EDM system has accuracy control over interelectrode gap, discharge energy, effective removal of debris particle from machining zone, etc.

6 Conclusion

This article discusses about the major areas of EDM-based research, i.e., effect of various EDM operating parameters, summary of various algorithmic work performed on EDM parameter optimization, review of state-of-the-art work performed over EDM, etc. Despite various studies and improvement of EDM concluded from numerous research papers, there is a requirement of continuous effort to optimize the performance measurement with respect to process variable such as voltage, pulse current, and pulse duration in EDM machining. Proper attention is required to monitor and control the EDM process. Therefore, suitable control system similar to fuzzy logic etc. should be used to maintain the machining process. It is also observed that research should be emphasized in the direction of online monitoring of the EDM process for better machining efficiency and improved performance.

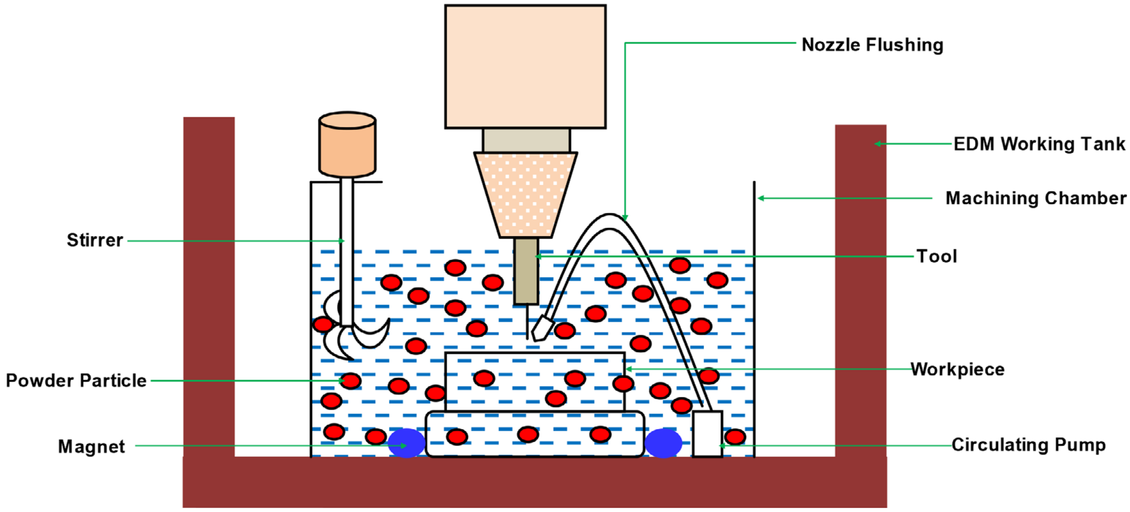

Fig. 6. Schematic of PMEDM setup.

Furthermore, advancement in EDM technology has been discussed by reviewing the modification of conventional EDM technique and its applications in other fields.

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