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ORIGINAL ARTICLE

A review on recent developments in machining methods based on electrical discharge phenomena

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Abstract The process of electrical discharge machining (EDM) is one of the modern machining processes that machining stiff and high-strength parts such as ceramics and heat-treated steels, which traditional methods cannot be successful in their materials removal, is the most important applications of the this process. Deep drilling, machining inclined surfaces and small-scaled machining are the other applications of this process. Despite the unique applications of this method of machining, low materials removal rate (MRR), high surface roughness (SR), high tool wear rate (TWR), formation of recast layer on workpieces surfaces (that is location of defects and cracks) and environmental problems are the main problems and limitations of this process. 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.

Keywords EDM · Dry EDM · Near dry EDM · Magnetic field assisted EDM · Ultrasonic vibrations assisted EDM · Powder mixed EDM

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1 Introduction

The base of electrical discharge machining (EDM) process was first proposed in 1770 by English chemist named Joseph Priestley, when he discovered the Erosive feature of electrical sparks. The EDM process in its present form was introduced many years after Priestley in 1943 by Lazarenko brothers [1].

In the EDM process, the tool moves toward workpiece until the gap distance between the tool and workpiece becomes small enough for ionization of dielectric fluid by applied voltage [2]. With ionization of dielectric in the gap distance, the electric current is established between the tool and the workpiece in the short time and is discharging in the gap containing fluid dielectric [3, 4]. With conversion of electrical energy into thermal energy, the temperature in plasma channels created between the tool and the workpiece reaches to 8000 – 12,000 °C and causes to melting the workpiece and the tool. With cutting off the electrical current, plasma channel extends and causes to sudden drop in temperature and jumping out the molten material from the workpiece and tool surfaces [5–8].

Electrical discharge machining is one of the most widely used non-traditional machining processes which use thermal energy for machining [9–11]. This process plays a significant role in modern machining industries especially in the case of machining of hard and high strength but electrical conductive parts, however some efforts were done for machining of non-conductive materials such as ceramics like zirconia ($ZrO2$) and alumina ($Al2O3$) [12–15], too.

The applications of EDM process which distinguish this method from other machining methods are as below.

In milling of materials with ordinary cutting tools, the workpiece hardness should be less than 30–35 HRC [16], while in the case of EDM process, the heat-treated materials with higher hardness can be machined. So, the materials can be heat-treated before machining and the dimensional changes after heat-treatment which is the negative point of heat-treatment after machining in the case of traditional machining (like milling) were omitted using EDM process [17].

Using a multi-electrode system for batch production of parts can be performed in EDM process which reduces the production time and costs [18].

Due to non-collision of the workpiece and tool in this process, the small scales machining up to 0.1 mm are possible with this process and there are no problems such as vibration, chatter, and mechanical stresses [19]. Ability of EDM process in micro machining (drilling micro holes or machining micro shafts and complex three-dimensional micro-cavities) of materials as small as 5 μm, [20], is not comparable with mechanical drilling which can machine micro holes up to 70 μm or laser machining which can only machine micro holes up to 40 μm [21].

Machining modern composite materials like Al2O3/6061Al and WC–Co (tungsten carbide–cobalt) composites which were developed in recent decades is another application of EDM process [22, 23].

Besides the most applications of EDM process, this method has some limitations such as creating surface cracks, metallurgical changes on surface and subsurface regions, heat affected zone (HAZ), and recast layer on machined surface [24–28]. So, many researchers invented and used some new machining methods based on EDM process such as dry and near dry EDM, magnetic field assisted EDM, powder mixed EDM, and ultrasonic vibrations assisted EDM in order to solve the EDM process problems and limitations. This paper has reviewed dry and near dry EDM, magnetic field assisted EDM, ultrasonic vibrations assisted EDM, and powder mixed EDM in order to classify the works have been done in these fields and demonstrate the investigations can be performed in future studies.

2 Dry EDM

Dry EDM is employed a gas as dielectric medium instead of liquid in conventional EDM. In this process, flowing of gaseous dielectric through rotating pipe tool flushed debris from gap distance as shown in Fig. 1. This process is an environmental friendly process as compared with wet EDM while that is simplicity is another advantage of dry EDM. However, because of low density of the gaseous dielectric, the MRR obtained by this process is lower (except using oxygen gas as dielectric medium) and obtained SR is higher due to debris reattachment [30–34].

Dry electrical discharge process has other applications, besides machining. Wang et al. [35] have used dry-electrical discharge to truing and dressing of metal bonded diamond wheel in order to decrease the wear of diamond dresser and increase truing accuracy of diamond wheel as compared with conventional mechanical truing methods.

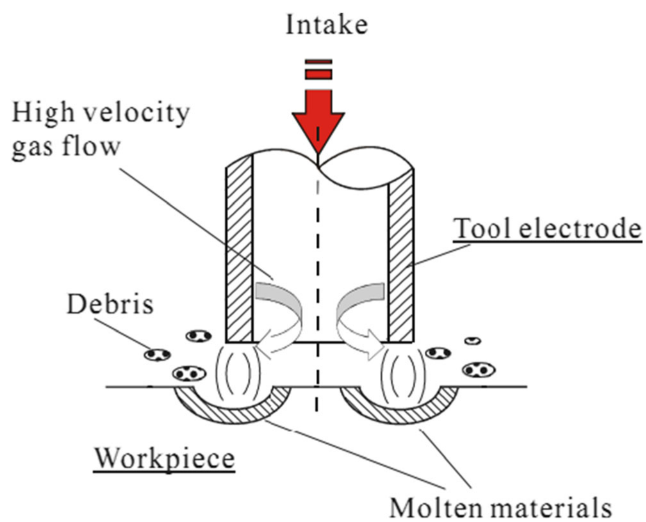


Fig. 1 Schematic demonstration of dry EDM process [29]

2.1 Ultrasonic vibrations assisted dry EDM

Due to an improvement in debris disposal and so decreasing the amount of re-solidified and reattached molten materials on workpiece surface, MRR is increased in ultrasonic vibrations assisted dry EDM process [36]. Zhang et al. [37, 38] have developed a theoretical model for predicting MRR in ultrasonic vibrations assisted dry EDM process. The machining of cemented carbide by ultrasonic vibrations assisted dry EDM process has studied by Xu et al. [39]. They have studied the material removal mechanism of cemented carbide and the mechanisms of creating of micro-cracks on machined surfaces in this hybrid process and concluded the generation of micro-cracks depends on electrical process parameters and properties of cemented carbide such as melting point, thermal conductivity, hardness and etc. Li and Zhu [40] have investigated the machining performance of ultrasonic induced workpiece vibration micro dry EDM and resulted that due to an improvement of debris flushing and so decreasing the number of abnormal pulses like arc by workpiece vibration, MRR is increased and TWR is decreased.

2.2 Micro dry EDM

Micro dry EDM process by external blowing mode based on RC pulse generator was studied by Li and Zhu [40]. Saleh et al. [41] have investigated micro dry EDM of vertically aligned carbon nano-tube (CNT) forests with reverse polarity in order to obtain higher precision in the patterned microstructures. They found that this method created higher discharge currents in the process, due to effective field-emission from

CNTs so the process can be performed at very low discharge energies. According to their results, this new method leads to faster, cleaner, and more stable process with higher precision, higher aspect-ratio micro patterning in the forests, and smoother machined surfaces.

2.3 Comparative study of dry EDM and wet EDM

ZhanBo et al. [42] have compared the machining of cemented carbide materials by dry EDM milling, oil EDM milling, and oil die sinking EDM and resulted that dry EDM milling has lower machining time, higher MRR, and lower TWR than oil EDM milling. Also, although the machining time of oil die sinking EDM is lower than dry EDM milling, but due to the long required time for preparation of tool in oil die sinking EDM, dry EDM milling is suitable for machining of difficult to machined materials like cemented carbide. Analyzes the thermal field of single pulse of dry EDM as compared with wet EDM was performed by Wang et al. [43], in order to discover the machining properties of dry EDM process by FEM software ANSYS. They simulated thermal strain graph affected by instantaneous high temperature and crater size of single spark. Obtaining crater size is helpful for predicting MRR, TWR, and SR and thermal strain graph is useful for analyzing organizational structure and residual stress and also to understand mechanical properties of machined surface.

2.4 Tool design

The sufficient space for flow of gaseous dielectric is provided and so the debris disposal is done properly and MRR is increased while TWR and the amount of attached debris particles on tools are decreased in dry EDM process using tools with peripheral [44]. Saha and Choudhury [45] introduced the dry EDM process as a environment-friendly process and designed the tool with optimum number of holes which maximize MRR and minimize the SR. They developed empirical models for MRR, SR, and TWR.

2.5 Gap state control

Lu et al. [46] developed a software and hardware system in order to provide the ability of detecting and controlling of gap state, automatically and also to establish a closed-loop gap state control system in dry EDM process (by joining a reference voltage adjustment module into the traditional reference voltage comparison gap state control system). According to their results, the new gap state control method improved the machining efficiency and machining accuracy of this process and also improved the automaticity of this process.

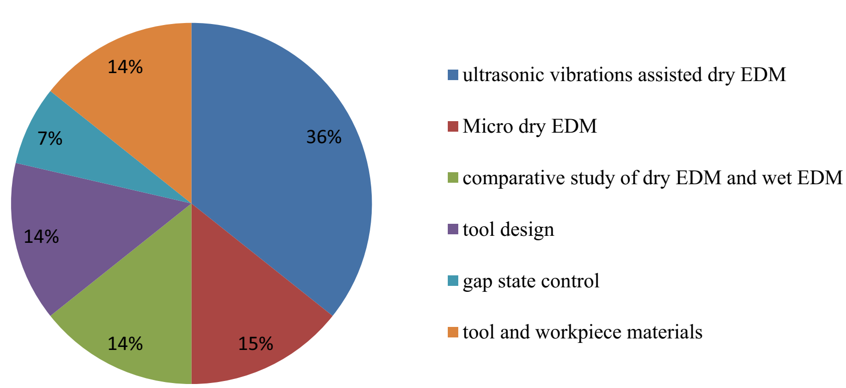
2.6 Tool and workpiece materials

Electrode and workpiece materials are one of important factors influencing electrical discharge machining process performances. Li et al. [47] performed a series of experiments in dry EDM process to find the suitable tool and workpiece materials which have the best machining performance. Also, Jia et al. [48] investigated the different tool materials (copper and graphite) in dry EDM process and studied their effects on MRR and SR. Their purpose was to achieve a high material removal rate at roughing operations and fine surface finish at finishing operations.

2.7 Remarks

Dry EDM was proposed by Kunieda and Yoshida in 1997 [49], firstly. This process is an environmental friendly process and does not create environmental problem induced by EDM process. The low MRR obtained by this process is one of the most important problems of this process, so the investigators used oxygen gas as dielectric medium in order to solve this problem, however still higher SR and lower surface integrity limits the usage of this process. According to Fig. 2, from studies conducted about dry EDM process during year 1997 to 2015, 35.7 % are related to ultrasonic vibrations assisted dry EDM, 14.3 % are about micro dry EDM, 14.3 % are narrated to comparative study of dry EDM and wet EDM, 14.3 %

Fig. 2 Research studies conducted in dry EDM



are about tool design, 7.1 % have connected with gap state control, and 14.3 % are related to tool and workpiece materials.

3 Near dry EDM

The near dry EDM process (Fig. 3) is a process in which a mixture of a gas and a liquid is used as dielectric medium. In this process, a tube-shaped rotating tool is used and the high speed dielectric is sprayed through the hole in the tool on the workpiece surface and with establishing electrical current between the tool and workpiece, machining operations is performed. The presence of liquid phase at dielectric medium helps to solidify and flush away the molten materials and so leads to higher MRR and lower SR due to reduction of debris reattachment [50].

3.1 Comparative study of near dry EDM with dry EDM and wet EDM

Kao et al. [51] have compared the machining time and dimensional accuracy of wet, dry, and near dry EDM process and found that the machining time of dry EDM process is longer than near dry EDM and the machining time of near dry EDM is a little higher than wet EDM to drill a specific hole while dry EDM process has intense debris deposition problem, which creates a tapered hole. The tapered hole is created at wet EDM but not as significant as dry EDM while the smallest taper in holes is archived by near dry EDM and no debris deposition is observed in near dry EDM, because water–air mixture has a better flushing capability than the air jet in dry EDM. The near dry EDM process with oxygen-water mixture as dielectric medium was studied by Kunieda and Furuoya [52], as compared with wet EDM with water dielectric. According to their results, near dry EDM leads to higher stock removal rate because of larger volume of discharge craters and more common happening of discharges. Jia et al. [48] studied near dry EDM milling process in compared with dry EDM process, to achieve a high MRR and low SR for roughing and finishing operations. According to their results, near dry EDM process created smoother surface under low discharge energy and good machining stability as compared with dry EDM.

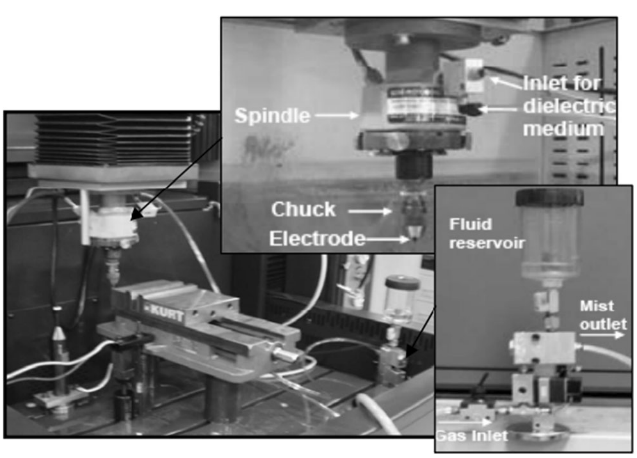


Fig. 3 Near dry EDM process equipments [50]

3.2 Dielectric fluid and electrode material

Jia et al. [48] have investigated the different tool materials and dielectric mediums in near dry EDM process. Jia et al. [53] added an electrical resistance into near dry EDM power generator to reduce the surface roughness and studied the effects of dielectric fluid, electrode material, and pulse energy on MRR and SR. The application of water-oxygen and water-air as dielectric mists in near dry wire-cut electrical discharge machining was investigated by Boopathi [54]. They resulted that the MRR obtained by oxygen mist dielectric is 19.8 % more than air-mist dielectric while, the obtained SR in the air-mist dielectric is 17.38 % higher than oxygen-mist dielectric.

3.3 Powder mixed near dry EDM

Powder mixed near dry EDM leads to higher MRR and lower SR as compared with dry and near dry EDM processes [55]. Bai et al. [56] have analyzed the material removal mechanisms of powder mixed near dry EDM process. The principle of material removal in powder mixed near dry EDM and the effects of residual heat on MRR in this process was investigated by Bai et al. [57]. They proposed this process deionization principle and the concept of superfluous residual heat. They studied the effects of this process parameters such as peak current, pulse on time, pulse off time, flow rate, tool rotational speed, air pressure, and powder concentration on MRR with two different tool materials (copper and brass) and two workpieces (45 carbon steel and W18Cr4V) based on the deionization principle of process.

3.4 Gap control strategy and tool path planning

The conventional gap control strategy only allows the retraction of the tool in the direction of machining path that has problem when the tool is not perpendicular to the workpiece, while the new gap control strategy is more efficient and with using a high speed piezoelectric actuator is capable of retracting the electrode in its axial direction and because of this capability, this strategy can enlarge the gap distance adequately to faster recovery of average gap voltage and enhance EDM efficiency [58]. The new strategy of tool path planning for five-axis near dry EDM with tubular electrode and a lead angle was investigated by Fujiki et al. [59], in order to avoid the leakage of dielectric medium from the tubular electrode and to achieve higher MRR. They performed a series of experiments to validate the new proposed strategy which predicts the path planning.

3.5 Near-dry wire-cut EDM

The pulse-width, liquid–gas pressure, and discharge current are the most important parameters for achieving high MRR and low SR in near dry wire cut EDM [54]. The near dry wire EDM of polycrystalline diamond coated tungsten carbide was studied by Jia et al. [60]. According to their results, near-dry wire EDM generated lower pollution and surface with lower roughness as compared with wire EDM although the MRR obtained by wire EDM is higher.

3.6 Electrode orientation

Fujiki et al. [61], in their study about the effects of electrode orientation (electrode lead and tilt angles) and fluid flow rate on material removal rate, tool wear ratio, and surface roughness in near dry EDM milling process, have developed a computational fluid dynamics (CFD) model to predict the dielectric fluid flow rate in the gap distance and correlated that with MRR obtained by experiments. They found the optimum lead angle, which maximized material removal rate and minimized tool electrode wear ratio. Also, according to their results, the tilt angle does not have any influence on the surface roughness and can be used to prevent gouging in finishing EDM.

3.7 Remarks

The EDM process is the main option for engineers to machining of hard, complex shapes, and small dimension components, but due to the high surface roughness and low surface integrity of parts produced by this process, a new process is needed in order to produce desired components. According to various researches, near dry EDM process that is based on EDM process is suitable process for this purpose. Near dry EDM has some advantages in comparison with dry EDM such as higher MRR, sharper cutting edge and less debris deposition, and in comparison with wet EDM, near dry EDM has higher material removal rate at low discharge energy and generates a smaller gap distance. However, near dry EDM creates a higher thermal load on the tool, which can break the wire in wire EDM and increases tool wear rate in EDM drilling. Also, near dry EDM process has no environmental concerns of EDM process caused by toxic dielectric disposal. This process was explored by Tanimura et al. in 1989 [62], firstly and then some researchers began to study of this process. According to Fig. 4, from different works which were done about near dry EDM process during year 1989 to 2015, 23.1 % are related to comparative study of near dry EDM with dry EDM and wet EDM, 23.1 % are about dielectric fluid and electrode material, 15.4 % have connected with powder mixed near dry EDM, 15.4 % are narrated to gap control strategy and tool path planning, 15.4 % are about near dry wire cut EDM and 7.6 % are related to electrode orientation.

4 Magnetic field assisted EDM

In magnetic field assisted EDM process, a magnetic field is applied around workpiece, tool electrode and machining gap and machining is performed in this condition, as shown in Fig. 5. Applying magnetic field in EDM process leads to an improvement in debris flushing from machining gap which reduces gap pollution and number of inactive pulses such as short and open circuit considering that these types of pulses do not remove any materials from workpiece and deteriorate surface integrity of machined workpiece [64–66].

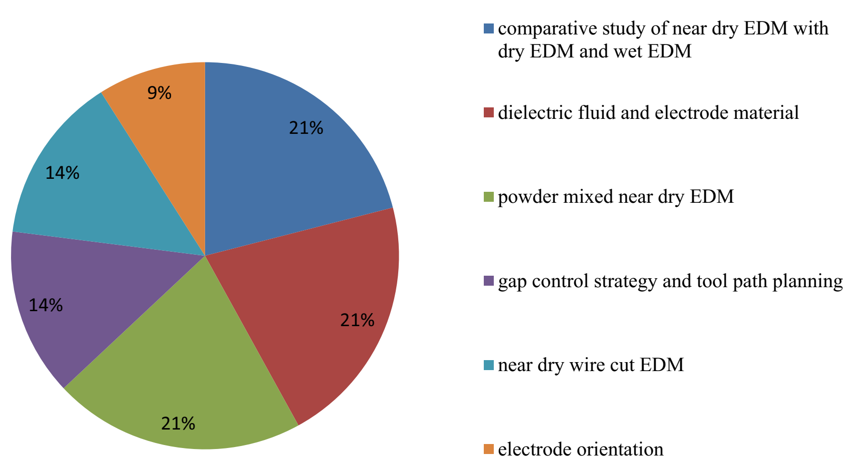


Fig. 4 The investigations performed in near dry EDM

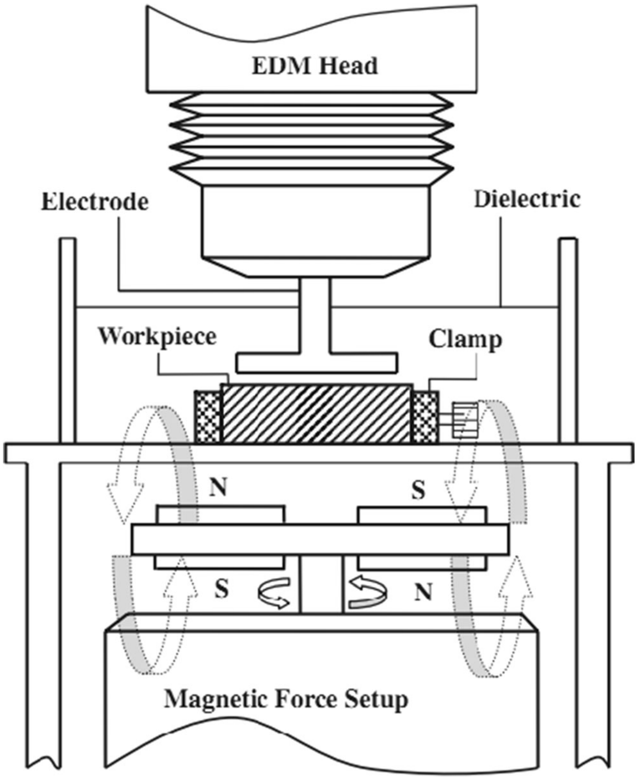


Fig. 5 Magnetic field assisted EDM process [63]

A magnetic force (Fm) due to magnetic field (BR) is applied on charged particles (electrons and protons) in addition to electrical force (Fe) due to electric field, by applying magnetic field for gap distance of EDM process, according to Fig. 6. So, the resultant forces FR (Lorentz forces) by an angle ϴ is acted on charged particles toward inside. Generation of Lorentz forces decreases plasma channel radius, increases electron density and consequently the energy of plasma channel, and also increases ionization at plasma channel because of increasing collisions between charged particles due to reduction in mean free path of electrons by constraining their motion. As a result, magnetic field assisted EDM leads to higher MRR [67].

4.1 Comparative study of magnetic field assisted EDM with conventional EDM

Due to an improvement in debris disposal from gap machining and decreasing gap pollution by applying magnetic field on gap distance of EDM process, magnetic force assisted EDM leads to lower number of abnormal pulses like arc, higher MRR (3 times) and lower SR, but TWR achieved by magnetic force assisted EDM is a little higher than conventional EDM [68]. Magnetic field assisted EDM has better machining stability as compared with conventional EDM. The bigger and deeper discharge craters are created at conventional EDM and also the surfaces machined by conventional EDM has more obvious micro-cracks. Also, recast layer thickness in conventional EDM is more than magnetic field assisted EDM [69].

4.2 Magnetic field assisted dry EDM

Teimouri and Baseri [70], in their study about magnetic field assisted dry EDM with ultrasonic vibrations of workpiece, investigated the effects of tools material, tools geometry (number of holes), applying magnetic field on gap distance of dry EDM and also the influences of process parameters such as pulse current, pulse on-time, pulse off-time, tool rotational speed, gas injection inlet pressure, and power of ultrasonic table on MRR, TWR, SR, and amount of created

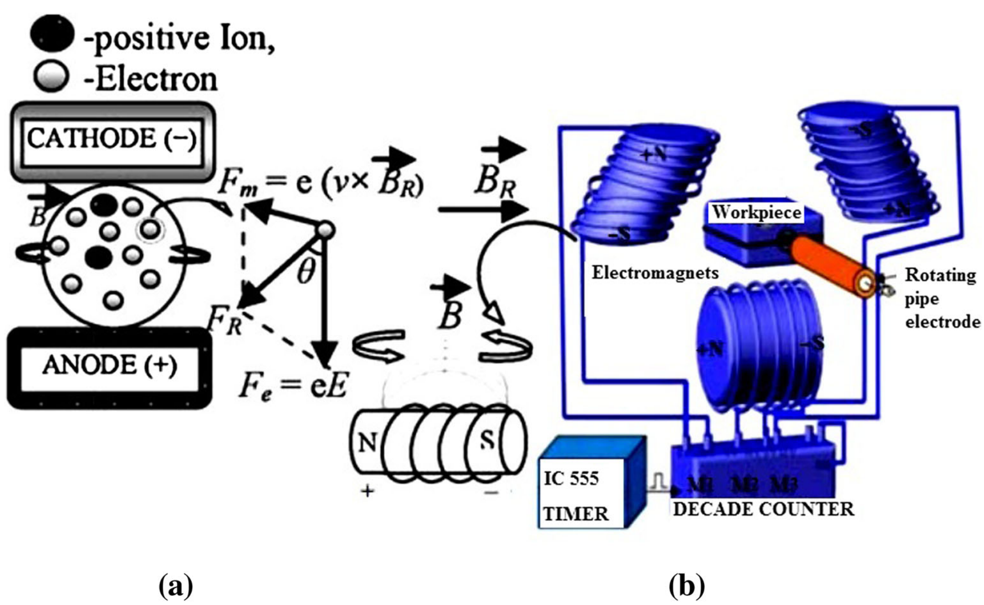


Fig. 6 **a** Schematic of tangential magnetic field and forces applied on gap distance of EDM process. **b** Application of pulsating electromagnetic field [67]

oversize. Applying pulsating magnetic field into gap distance in dry EDM process leads to increasing of MRR up to 130 % due to an increase in collisions between charged particles in plasma channel and generating Lorentz forces which leads to increase of plasma density, amount of ionizations, and so faster breakdown of plasma channel [67].

4.3 Magnetic field assisted micro EDM

Higher MRR and lower TWR are achieved by applying magnetic field around gap distance of EDM process in high-speed small hole drilling [71]. Heinz et al. [72] applied an external magnetic field in order to generate Lorentz force on molten materials and developed magnetic field assisted micro EDM for nonmagnetic materials and studied the effects of the Lorentz force on MRR by investigation of erosion efficiency, melt pool volume analysis, plasma temperature, electron density, and debris field characterization. According to their results by applying magnetic field and producing Lorentz force, MRR is increased up to nearly 50 % while they did not find any negative effects of Lorentz force on TWR. Yeo et al. [73] investigated magnetic field assisted micro EDM process in order to achieve higher aspect ratio micro holes. They found that applying magnetic field leads to better debris circulation and flushing, so the holes with higher depth can be achieved at magnetic assisted micro EDM as compared with conventional micro EDM while the surface roughness of side walls of drilled holes are equal nearly.

4.4 Magnetic field assisted wire EDM

Magnetic field assisted wire EDM process was investigated by Tomura and Kunieda [74]. They developed a two-dimensional finite element method (FEM) program considering electromagnetic induction in order to find the mechanism of applied electromagnetic force to wire in wire EDM process and calculated wire movement by analyzing the current density and magnetic flux density. They also found that the accurate simulation of workpiece shapes machined by wire EDM was achieved by considering the electromagnetic forces.

4.5 Remarks

Several investigations have studied magnetic force assisted finishing process in order to decrease surface roughness and improve manufacturing techniques, in recent decade [75–85]. However, these investigations only focused on the magnetic abrasive processes, some studies used magnetic field in EDM process and investigated magnetic force assisted EDM process, in order to improve the EDM performances by influencing the generated plasma channel in EDM process and gap conditions. De Bruijn et al. were the first investigators which applied magnetic field into EDM process in 1978 [86]. According to Fig. 7, between 24 reviewed works at this paper about magnetic field assisted EDM process, from 1978 to 2015, 28.6 % are related to comparative study of magnetic field assisted EDM with conventional EDM, 28.6 % have connected with magnetic field assisted dry EDM, 28.6 % are about magnetic field assisted micro EDM, and 14.2 % are related to magnetic field assisted wire EDM.

5 Ultrasonic vibrations assisted EDM (UEDM)

In ultrasonic vibrations assisted EDM, the workpiece, tool, or dielectric fluid is vibrated ultrasonically and machining operations is done in this condition as shown in Fig. 8. The debris ejection from machining gap is improved by applying vibrations on workpiece or tool which leads to lower abnormal pulses like arc. Decreasing gap pollution and arc pulses leads to higher MRR and lower SR [88–90].

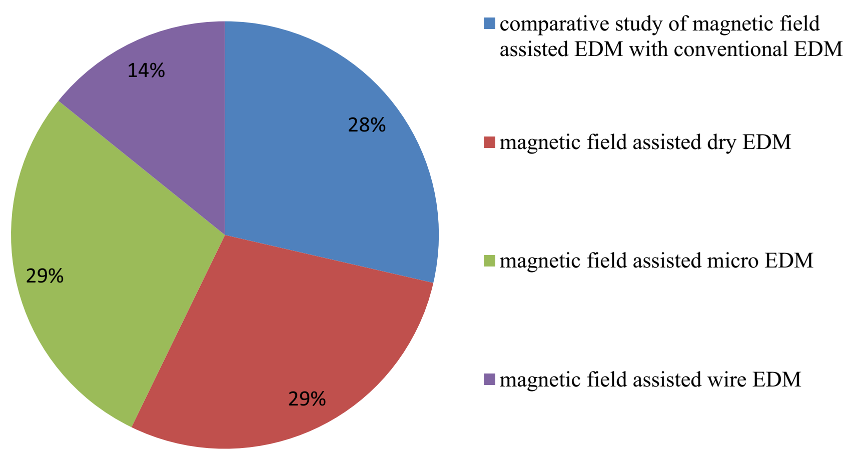


Fig. 7 The distribution of studies performed in magnetic field assisted EDM into different areas

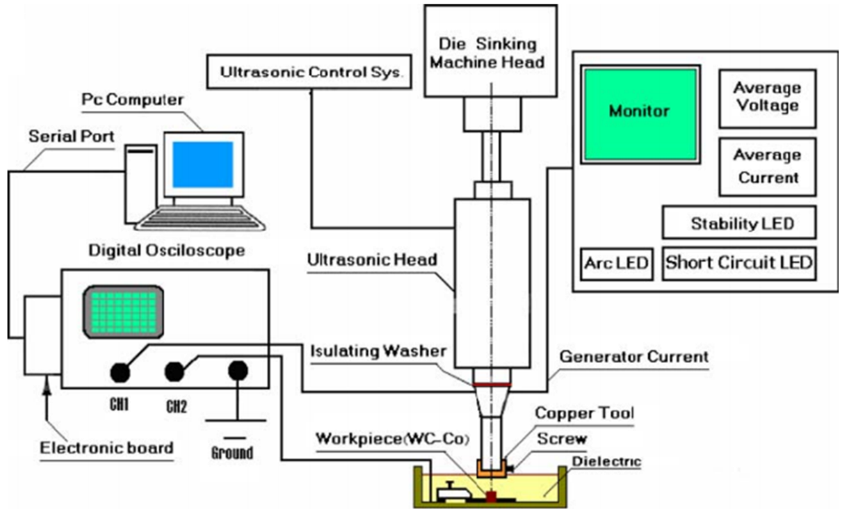


Fig. 8 Schematic demonstration of ultrasonic vibrations assisted EDM [87]

At ultrasonic vibrations assisted EDM process, applying vibrations to workpiece, tool, or dielectric medium has some effects as below [91, 92]:

- The polluted dielectric (containing debris) is pumped out by upward motion of workpiece and also the new and fresh dielectric is sucked inside the sparking zone by downward motion of the workpiece. The result of this phenomenon is reducing the amount of re-solidified layer on tool and workpiece surface and also number of abnormal pulses like arc.
- The ultrasonic vibrations of tool, workpiece, or dielectric cause better dielectric circulation and also better flushing away the debris due to vibrations and cavitations phenomenon which leads to higher MRR.
- The ultrasonic vibrations of tool, workpiece, or dielectric can prevent the accumulation of debris and carbon particles by changing the distribution of these particles and decreases the occurrence of short-circuits and abnormal pulses.

5.1 Numerically investigations of ultrasonic vibrations assisted EDM

By increasing the frequency and amplitude of tool vibrations in UEDM process, the rate of pressure drop inside the bubble and on the surface of the workpiece is enhanced, also due to an improvement of debris flushing resulted by applying ultrasonic vibrations on tool, MRR is increased [93]. Shervani-Tabar et al., in their investigation about ultrasonic vibrations assisted EDM [94], performed vapor bubble behavior computational simulation which is generated between the tool and the workpiece, using boundary integral equation method. Shervani-Tabar and Mobadersany [95] investigated the influences of ultrasonic vibrations of the tool, velocity fields, and pressure distribution in the dielectric fluid around the generated vapor bubble on the progress of the created bubble and its surrounded dielectric fluid behavior in EDM process numerically, using the boundary integral equation method. Simultaneous ultrasonic vibrations of the tool and the workpiece and also enhancing ultrasonic vibrations frequency and amplitude, increases the life time of the bubble and its growth and collapse rates and leads to the bubble extend to its maximum volume which causes to drop the pressure of bubble insides to its minimum amount, consequently and totally increases the amount of removed workpiece materials and improves MRR [96]. Shervani-Tabar et al. [97] investigated the dynamic behavior of the vapor bubble induced by electrical discharge in UEDM process after occurring necking when the bubble takes the shape of an hour-glass and divided into two parts which leads to creating two liquid jets moving toward workpiece and tool and collide them, numerically in three cases of tool and workpiece with flat surfaces, convex surfaces and concave surfaces.

5.2 Ultrasonic vibrations assisted micro EDM

The vibration of workpiece has important effects on machining performance of micro EDM process and the efficiency and aspect ratio of the hole machined by ultrasonic vibrations assisted micro EDM process are higher [98]. Chern et al. [99] developed a new micro-punching machine based on micro EDM process in order to creating micro holes with high precision and eliminating the eccentricity problems between the punch and the die. They applied ultrasonic vibrations to this new system and studied the vibrations assisted micro EDM process. EDM with ultralow discharge energy and ultrasonic vibrations of workpiece was studied by Egashira et al. [100]. These investigators used ultrasonic vibrations to improve the debris ejection from gap distance and reduce gap pollution and abnormal pulses due to using the ultralow discharge energy in EDM process. By setting the vibration amplitude of workpiece nearly equal to discharge gap, better machining results can be achieved in micro EDM process using the tool with non-circular cross section structures [101]. The machining performances is improved by adding carbon nano-fibers into dielectric in micro EDM process and applying ultrasonic vibrations on dielectric fluids due to the agitating and cloud cavitations effects of vibrations which leads to increasing debris ejection out of gap distances and avoiding tool material deposition on machined surface [102]. Zhao et al. [103] investigated drilling of deep and small holes on titanium alloy by ultrasonic vibrations assisted micro EDM process and studied the effects of applying ultrasonic vibrations on micro EDM process. They provided a wire electric discharge grinding unit which fabricates micro electrode on line during machining. They resulted that by applying ultrasonic vibrations into micro EDM process, the debris removal from gap distance is improved and also by using single notch micro electrode by mentioned electrode fabricating method, the spaces for debris ejection in drilling of small and deep holes is increased and totally the machining efficiency and performance is improved by decreasing gap distance pollutions and abnormal pulses with using these mechanisms. Due to a decrease in size of lateral gap width between the tool and workpiece by applying ultrasonic vibrations to machining fluid in micro EDM process, the TWR is reduced. Also, minimum machining time and TWR are achieved in hybrid ultrasonic vibrations assisted micro EDM process with rotating tool [91]. The workpiece is vibrated ultrasonically in micro EDM process by Chern and Chuang [104], in order to mass punching of micro holes. They also studied the effects of tools rotating in this process. Prihandana et al. [105] used micro-MoS2 powder in dielectric fluid and studied powder mixed micro EDM process with ultrasonic vibrations of dielectric fluid in order to increase MRR and improve the obtained surface quality by creating a flat surface without black carbon spots.

5.3 Combined electrical discharge machining (EDM) and ultrasonic machining (USM)

Yan et al. [106] investigated the drilling of micro holes with high aspect ratios in borosilicate glass with combination of micro EDM and micro USM process with rotating tool. Thoe et al. [107] studied the combination of USM and EDM process for machining of small holes less than 1 mm in diameter on ceramic coated nickel alloys. They showed that a force feedback control system for the production of these holes is necessary. Lin et al. [108] combined EDM and USM processes to machining titanium alloy (Ti-6Al-4V) in order to improve the machining efficiency and accuracy. According to their results, this hybrid machining method improved the debris removal and decreased the abnormal discharge which leads to higher MRR and lower recast layer thicknesses. Lin et al. [109] combined EDM and USM process to form a modified layer on the machined surface of Al-Zn-Mg aluminum alloy by adding the Sic particles into dielectric fluid to create a fortified solid solution in order to form mentioned modified layer. They resulted that positive polarity created grater silicone and carbon content on machined surface which leads to better surface modifications. This modified layer improved the hardness and wear resistance of machined surface.

5.4 Fuzzy approach to ultrasonic vibrations assisted EDM

The discharge parameters and the gap between tool and workpiece can be adjusted properly in UEDM process by using an adaptive fuzzy control system of a servomechanism which leads to increasing of surface quality, dimensional accuracy, and MRR [110]. Shabgard et al. [111] used a fuzzy based algorithm to propose a model to predict MRR, TWR, and SR obtained by EDM and UEDM process. This model can be used for selection of EDM and UEDM input parameters to achieve required MRR, TWR, and SR with better machining conditions and lower machining costs.

5.5 Comparative study of EDM and USM

Jianxin and Taichiu [112] investigated the obtained surface integrity of EDM, USM, and diamond saw cutting of ceramic composites. They compared the surface roughness, hardness, and topography of machined surfaces in these three processes. According to their results, EDM process created rougher surfaces with poor surface integrity with many cracks, craters, and a heat affected surface layer on machined surface. They found that surface integrity of USM and diamond saw cutting processes are better than EDM process under most of machining conditions. Also, the flexural strength and Weibull modulus of machined specimens by these processes is higher as compared with EDM process.

5.6 Remarks

Applying ultrasonic vibrations into workpiece and tool in EDM process is firstly investigated by Murthy and Philip in 1987 [113] and also by Kremer et al. in 1989 [92], in order to improve the debris ejection from gap distance and decrease gap pollution and abnormal pulses which resulting to solve the EDM process limitations and improve the performances of EDM process. According to Fig. 9, among 27 works about ultrasonic vibrations assisted EDM process from 1987 to 2015, which were reviewed at this paper, 18.5 % are related to numerically investigations of ultrasonic vibrations assisted EDM, 37 % are about ultrasonic vibrations assisted micro EDM, 14.8 % have connected with combined EDM and USM processes, 7.4 % are narrated to fuzzy approach to

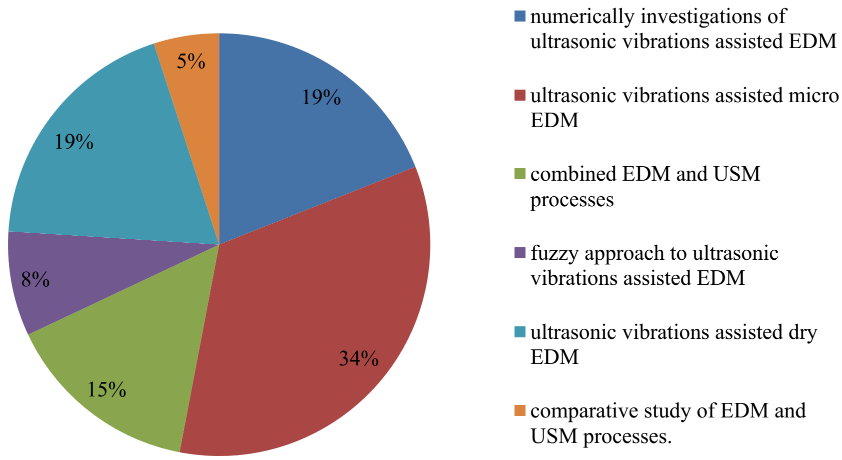


Fig. 9 Studies conducted in ultrasonic vibrations assisted EDM

ultrasonic vibrations assisted EDM, 18.5 % are about ultrasonic vibrations assisted dry EDM, and 3.8 % are related to comparative study of EDM and USM processes.

6 Powder mixed electrical discharge machining (PMEDM)

Powder mixed EDM is a new kind of EDM process. In this process, the electrically conductive powder is mixed in the dielectric fluid of EDM to improve EDM process performance by decreasing the insulating strength of the dielectric fluid and increasing the gap distance which leads to enhancing process stability and improving MRR and surface quality. The schematic of PMEDM experimental setup is illustrated in Fig. 10 [114].

Figure 11 shows the gap distance of powder mixed EDM which contains powder particles. The powder particles at gap distance get energized with applying voltage and come close to each other and arrange themselves in the form of chains (by applying electric forces under the sparking area). Formation of chains increases the bridging phenomena between tool and workpiece and thus, the gap voltage and insulating strength of the dielectric fluid are decreased and as a result the frequency of discharging is increased. So, the sparking occurred faster and leads to faster erosion from the workpiece surface. Also, the gap distance and the plasma channel radius is increased by adding powder particles to dielectric and so the electric density is decreased and the sparking is uniformly distributed between the powder particles which lead to generation of shallower craters on workpiece surface and as a result surface roughness is decreased and smoother surface is obtained [114].

6.1 MRR, TWR, and surface quality of PMEDM

A proper method for finish machining of free from surface and achieving mirror like free from surface in die making process

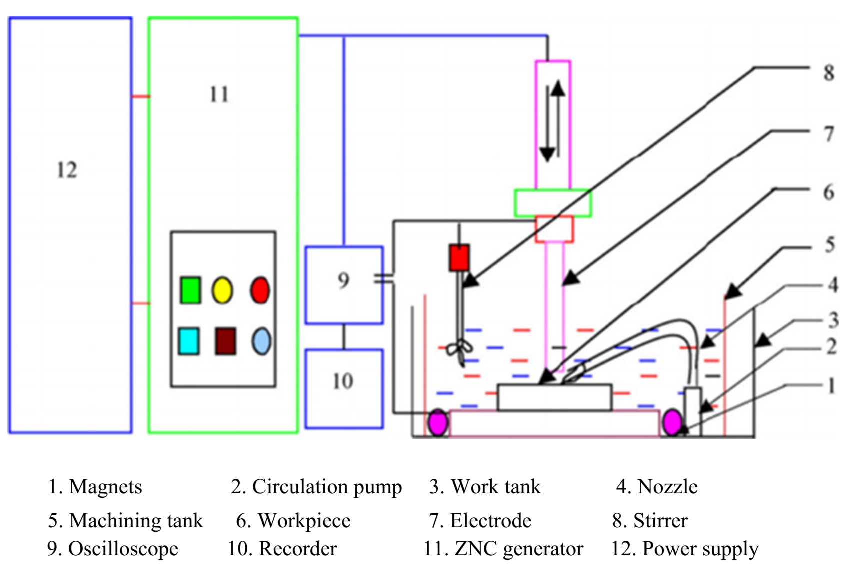


Fig. 10 Schematic illustration of PMEDM experimental setup [114]

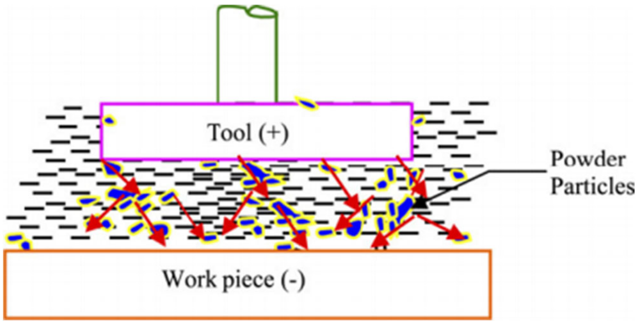


Fig. 11 Principle of powder mixed EDM [114]

is using silicon powder mixed EDM process [115]. Pecas and Henriques [116] studied powder mixed EDM process in compared with conventional EDM in order to achieve high quality surface. They investigated the effects of electrode area on surface roughness, crater size (width and depth), thickness of white layer and surface morphology in powder mixed and conventional EDM and resulted that better surface quality is achieved by using great electrode area and powder mixed EDM as compared with conventional EDM. These researchers added silicon powder particles in the dielectric fluid in EDM process in order to improve the performance of EDM process [117]. According to their results, the surface roughness is decreased and mirror like surface is obtained by this new approach because the presence of silicon powder decreases the generated craters diameter and also depth and melted material overflow. The surface roughness of PMEDM is lower, the corrosion resistance obtained by PMEDM is better and wear resistance and the hardness of machined surface by PMEDM is higher than EDM in machining of SiCp/Al composite and ASP-23 alloy steel [118]. Powder mixed EDM with different types of powder particles, workpiece materials, electrode polarity, and pulse parameters was studied by Wong et al. [119], in order to find the best combination of parameters to achieve mirror finish surfaces. Tzeng and Lee [120] added various powder particles with different thermo-physical properties such as aluminum (Al), chromium (Cr), copper (Cu), and silicon carbide (SiC) into dielectric fluid in EDM process and studied the effects of powder particles properties, concentration, and size on gap distance, MRR, and TWR in powder mixed EDM process. According to their results, the highest MRR and lowest TWR are achieved by smallest powder particle size in all type of powders. Ming and He [121] studied the MRR, TWR, and surface quality obtained by powder mixed EDM process. According to their results, adding powder to dielectric fluid can increase the discharge gap which leads to more even discharges, enhance the alloy elements on the surface and microhardness of machined surface and also can decrease the thickness of recast layer and generated cracks on the surface. Jabbaripour et al. [122, 123] investigated the effects of different powder particles type such as aluminum, chrome, silicon carbide, graphite, and iron on MRR, surface roughness and topography and electrochemical corrosion resistance of machined surfaces in powder mixed EDM of γ-TiAl inter-metallic and compared the PMEDM and conventional EDM. According to their results, the MRR and electrochemical corrosion resistance of machined surfaces by PMEDM are higher than conventional EDM and the surface roughness obtained by PMEDM is lower. Powder mixed EDM process of SKD-11 by using aluminum (Al), chromium (Cr), copper (Cu), and silicon carbide (SiC) powders suspended in oil dielectric fluid was studied by Tzeng et al. [124]. According to their results, smaller size of powder particles leads to better surface finish but thicker recast layer. Also, they found that Al powder generates the best surface finish and the thinnest recast layer on machined surfaces as compared with other powders, while using copper powder and also performing process without any additives leads to the worst surface quality. Wu et al. [125] added Al powder and surfactant to dielectric fluid in EDM process to improve the surface finish of SKD steel. A surfactant can decrease the agglomeration of Al powder particles in dielectric fluid and leads to homogenous distribution of powder particles in dielectric and can decrease machined surface roughness and the thickness of recast layer. Also, they investigated the effects of process parameters on surface roughness. Although the machining efficiency and surface roughness of PMEDM are lower than conventional EDM in rough operations due to easier breakdown of dielectric and increasing gap distance which leads to much loss of discharge energy in gap distance and reduction of debris removal from machining gap, but by proper selecting of machining parameters (higher peak current and lower pulse width) it can be possible to achieve higher machining efficiency and lower surface roughness as compared with conventional EDM in rough machining [126].

6.2 Surface modification with powder mixed EDM

Surface modification of workpieces using EDM process is achieved by transfer of eroded tool material into workpiece surface, using powder-mixed dielectric fluid or breakdown of the hydrocarbon dielectric which transfer carbon to plasma channel. This approach is considered by several researchers in last decade [127–130]. Chen et al. [127] used micro-current EDM process and deionized water mixed with titanium (Ti) powder as dielectric solvent in order to modify surface characteristic of pure Ti which is used in dental implants. They found that the surface cracks, micro-cracks, and volcano-like structures for modified Ti are decreased and the thickness of the recast layer is increased by increasing Ti powder concentration. Also, by creating TiO phase in recast layer, a hydro-philicity surface is generated in certain working conditions and the wettability on the surfaces of Ti is enhanced which is essential for dental implants application. Kumara and Batra [128] investigated three die steel materials surface modifications using tungsten powder mixed EDM process. According to their results, by transferring tungsten and carbon to workpieces surface during process and creating tungsten carbide (WC and W_2C), the micro-hardness is increased more than 100 % in all kind of die steels. Janmanee and Muttamara [129] used powder mixed EDM process with oil as dielectric fluid which was mixed with titanium powder for coating purpose and formed a titanium coating layer onto a tungsten carbide surface to modify tungsten carbide surface characteristic. Surface modifications of carbon steel (AISI-1049) by powder mixed EDM process with a green compact electrode were studied by Furutani et al. [130]. They added titanium alloy powder into dielectric fluid (oil) in EDM to create TiC layer on the workpiece surface. They investigated different electrode shapes for this purpose. According to their results, the new TiC layer can be formed on workpiece surface by using a thin electrode while the powder concentration remains high in this condition. Also, a wider layer with uniform thickness can be achieved by using a gear shaped rotating electrode.

6.3 Optimization and numerical simulation of powder mixed EDM

Wu et al. [125], in their study about PMEDM process, used Taguchi method to optimize the surface roughness. Kansal et al. [131] used response surface methodology method to proper an empirical model in order to optimize the process parameters of silicon powder mixed EDM process. A finite element method was used by Kansal et al. [132] to develop a symmetric two-dimensional model for powder mixed EDM process in order to prediction of thermal behavior and material removal mechanism in this process. According their simulation results, the dimension of created craters on workpiece surface in powder mixed EDM is smaller than conventional EDM.

6.4 Powder mixed micro EDM

Klocke et al. [133] investigated the effects of adding different kinds of powder particles (Al and Si) into dielectric fluid and capacitor which is connected parallel to the gap distance on thermal spread in dielectric, recast layer, and heat affected zone in micro sinking EDM process. Chow et al. [134] studied micro-slit EDM process with various dielectric fluids such as kerosene, kerosene with aluminum powder, and kerosene with SiC powder in compared with together in the case of material removal depth, expansion of slit, electrode wear, and surface roughness. The machining of micro-slit in order to achieve a green manufacturing technology without environmental pollution was developed by adding SiC powder to the pure water as dielectric fluid in EDM process [135]. Ultrasonic vibrations assisted micro-MoS2 powder mixed micro EDM process was investigated by Prihandana et al. [105], in order to increase the EDM process performance.

6.5 Using powder in other electro discharge processes

Shabgard and Najafabadi [136] used electro discharge process with tungsten and graphite electrodes and kerosene and deionized water as dielectric fluid, in order to synthesized nanostructured tungsten carbide (WC) powder. They studied the effects of current and pulse duration on the amount, size, structure, phases, and morphological properties of produced powder. Han et al. [137] used conductive particles (graphite powder which has good thermal and electrical conductivity) in the electrolyte in electro-chemical discharge machining (ECDM) process in order to improve the obtained surface integrity.

6.6 Remarks

The powder mixed EDM process is an innovations in EDM fields which was introduced and studied by Jeswani in 1981 [138], firstly. In this process, because of increasing the insulating strength of dielectric fluid and so the gap distance by adding powder particles into dielectric fluid, the stability of process and process performance are enhanced. According to Fig. 12, among reviewed studies about powder mixed EDM at this paper from 1981 to 2015, 42 % is about MRR, TWR, and surface quality of PMEDM, 14 % are related to surface modification with powder mixed EDM, 11 % are narrated to optimization and numerical simulation of powder mixed EDM, 11 % are about powder mixed near dry EDM, 14 % are related to powder mixed micro EDM, and 8 % are about using powder in other electro discharge processes.

7 Future EDM research direction

The authors have classified the different new trends in EDM process as mentioned before into five different major areas. Table 1 shows this classification, in order to discuss and introduce the possible future research directions and areas.So, the future possible advancements,

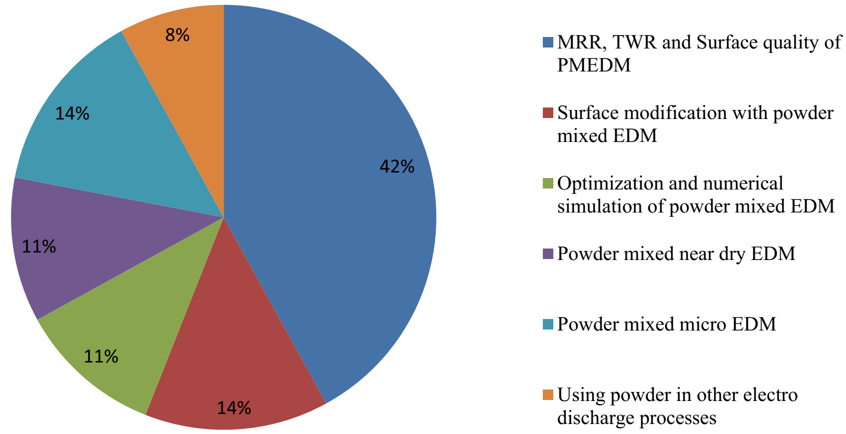


Fig. 12 Investigations which are performed in powder mixed EDM process area

research opportunities, and challenges in the area of EDM process can be listed as below:

- Realize of the fundamental science and behavior of listed processes at Table 1 in order to expanding their usages to industries.
- Modeling, optimization, and also automation of listed processes at Table 1 for satisfying various demands. Different theoretical models for describing behavior of EDM process have been proposed by researchers with many assumptions which make some errors in modeling. So, some future works can be focused on modeling of EDM process and also the mentioned new processes at Table 1, with fewer simplifier assumptions which reduce the modeling error.
- Development of listed processes at Table 1 for nano-scale machining regarding the special properties of these processes.
- The effects of current and pulse duration on MRR, TWR, and surface integrity of listed processes at Table 1 were studied but the influence of other electrical input parameters such as polarity, pulse interval and etc. was not focused much.
- Surface modification by listed processes at Table 1 was not focused much except in the case of powder mixed EDM process and can be a good research area for investigators considering that the surface modification is a new and important works can be done by these processes while it is at experimental stage yet and many issues should be noted to be acceptable for industries.
- Try to invent other new hybrid processes based on electrical discharge phenomena which can improve the EDM process performance.
- At multi spark EDM and multi electrode EDM which are relatively new techniques, the EDM process can be replaced by listed processes at Table 1 in order to more improve of multi spark EDM and multi-electrode EDM processes performance.

Table 1 New trends in EDM process which were discussed in this study

#	New process
1	Dry EDM
2	Near dry EDM
3	Magnetic field assisted EDM
4	Ultrasonic vibrations assisted EDM
5	Powder mixed EDM

8 Summary

EDM process performs great function in industry due to this process ability in machining hard materials and complex parts. In this paper, some new hybrid machining process based on EDM process such as dry EDM, near dry EDM, magnetic field assisted EDM, ultrasonic vibrations assisted EDM, and powder mixed EDM was reviewed and the investigations about them were studied briefly. The investigations about each process were divided into some subsets and each subset includes the studies performed in recent years. This paper revealed the percent of investigations in each subset and can be a good guide for future studies by showing the areas which did not study or less focused.

The purpose of each new hybrid machining process is improving the EDM process ability and efficiency and also decreasing this process limitations and problems. Dry EDM is an environmental friendly process however with lower MRR as compared with conventional EDM. Near dry EDM is an environmental friendly process and also is more effective than EDM process especially in finishing process. Magnetic field assisted EDM has higher MRR and lower SR as compared with conventional EDM due to the influence of magnetic field on gap conditions and plasma channel. Ultrasonic vibrations assisted EDM improves the debris removal from machining gap and leads to better machining performance and powder mixed EDM increases process stability and so the performance of EDM process.

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