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Steps towards green manufacturing through EDM process: A review

Nishant K. Singh[1*], Pulak M. Pandey[3], K.K. Singh[2] and Manish K. Sharma[1]

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*Corresponding author: Nishant K. Singh, Department of Mechanical Engineering, Hindustan College of Science and Technology, Mathura, India
E-mail: nishant.singh78@gmail.com

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Abstract: This paper focuses on the current machining process initiatives, carried out by various researchers relevant to the environmental aspects, thereafter predicting EDM performances. electrical discharge machining (EDM) is widely used unconventional machining method, because of its ability to process very hard material with precision. In thermo-electric process, control spark generation between electrodes causes material removal; however, application of hydrocarbon oil based dielectric fluid is an issue of environmental disruption. Replacement of dielectric to rectify the problem is one of the main concerns in EDM research. This paper highlights dry-EDM, near-dry EDM and EDM in water, conceived as an environment friendly alteration in the oil EDM process referred as a green EDM process. The work provides a thorough review of dry, near-dry EDM and EDM in water as a process, where the target is to endeavor dielectric fluids which could be the alternative to replace hydrocarbon oil. It is perceived that water and gas based dielectrics could take over oil-based fluids in EDM applications. Novel technological advances in dry EDM machining processes, which deliberate the advanced stage of a technology in academic and industrial research is briefly reviewed and an outline for the future work has been paved.

Subjects: Clean Technologies; Environmental; Pollution

Keywords: green; hydrocarbon oil; dry-EDM; environment; water; dielectric

1. Introduction

Electrical discharge machining (EDM) involves discharge of the spark between electrically conductive workpiece and tool electrode to erode the work material. The sparking in EDM is controlled by DC pulses while application of direct current ionizes dielectric fluid within the spark gap (Benedict, 1987). EDM eradicates issues of induced mechanical stresses and vibration while machining, as it

ABOUT THE AUTHOR

Nishant K. Singh is a PhD research scholar at IIT (ISM) Dhanbad and is currently working in the field of gas assisted EDM. He has obtained his Masters in Mechanical Engineering and BTech in Mechanical engineering from Delhi College of Engineering, Delhi. His research interests are sustainable manufacturing, micro manufacturing and non-conventional machining processes.

PUBLIC INTEREST STATEMENT

The environmental impact on machining is being extensively studied among the researchers. In EDM, application of hydrocarbon oil based dielectric fluid is an issue of environmental disruption. Replacement of dielectric to rectify the problem is one of the main concerns in EDM research. The work provides a thorough review of dry, near-dry EDM and EDM in water as a process, where the target is to endeavor dielectric fluids which could be the alternative to replace hydrocarbon oil. It is perceived that water and gas based dielectrics could take over oil-based fluids in EDM applications.

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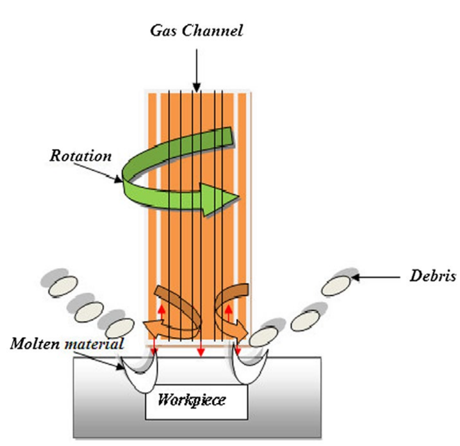
doesn't have a physical contact with tool electrode and the specimen (Kumar, Singh, Batish, & Singh, 2012). EDM has considerable superiority over conventional machining to manipulating work piece of hard materials and complex shapes (Pandit & Rajurkar, 1981). However, there is an abundance of deprivations, as it amalgamates environment pollution and being harmful to the surroundings (Li, 1989). EDM operations extensively use kerosene-based dielectric liquid. The perseverance and the competency of the EDM process, depends upon the use of liquid dielectric. The liquid dielectric provides a cooling medium in discharge gap as well as flushing of debris from the machining zone, thereby play significant roles during material removal mechanism (Eckman & Williams, 1960; Hoh, 1963; Koenig & Siebers, 1993; Zolotykh, 1959). However, during the EDM process, oil-based dielectric liquid decomposes and produce vapor, which is harmful to the operator and contaminate the environment (Han & Kunieda, 2004). Even so, when hydrocarbon oil is used health, safety and the environment become vital aspects (Leão & Pashby, 2004). Present research focuses on development of less or no-polluting EDM techniques, which may protect the environment and facilitates substantial high MRR, low TWR, better surface accuracy and fine surface finish (Beşliu, Schulze, Coteață, & Amarandei, 2010).

2. Green EDM Machining

To overcome the pollution and production of harmful vapor throughout EDM machining using hydrocarbon dielectric, the EDM process is further refined and a new novel method was proposed its name was given as dry-EDM (DEDM) process. In DEDM, compressed gas or air passes through a thin-walled tubular pipe, wherever compressed gas cools the inter electrode gap and thus relived the debris from the machining zone (Kunieda, Furuoya, & Taniguchi, 1991; Kunieda & Yoshida, 1997). DEDM is considered as an environmentally beneficial technique as a result of the absence of mineral oil-based liquid dielectric and environmentally harmful oil-based dielectric wastes doesn't seem to be raised, as a result of inheritance of these properties DEDM process is also known as a green EDM process. Likewise, the procedure doesn't 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 improving the efficiency of process and reducing the operating cost.

A short technical paper presented use of gas based EDM by Armani and Cassidenti, NASA in1985. Argon or helium gas was applied as a dielectric for drilling a hole by tubular copper electrode (Ramani & Cassidenti, 1985). However, in 1997 Kunieda and Yoshida proposed new machining method known as EDM in gas (Refer Figure 1). They proposed to decreased pollution by using gas rather than kerosene based dielectrics. Afterwards, it was being studied as method of good prospects (Kunieda et al., 1991).

Figure 1. The principle of dry EDM (Kunieda et al., 1991).



Most likely advantages of DEDM process are negligible tool wear, low residual stresses and better precision. For machine makers and machine user's practical application of the DEDM process strive many advantages like simplicity in machine building, it does not require advanced and spacious dielectric circulation and cooling mechanism, thus contributes to reduction in manufacturing cost.

Considering concrete advantages of dry machining processes, as shown in Figure 2, firms and researchers concerned with the evolution of electro discharge machining primarily aiming towards minimizing the use of hydrocarbon dielectric fluids, either by replacing it with gas, pure water or water-emulsion solutions (Skrabalak & Kozak, 2010). Though, methodology seems promising, however, needs furthermore exhaustive investigation before it could see widespread application at industrial scale.

An organized investigation of dry EDM is important for interpretation of the process, with some elementary input and output factors. From Figure 3, it can be seen that, a number of the input factors taken into account are the characteristics of the dielectric fluid, especially, electrical and machining parameters. While output parameters, are MRR, TWR, SR and pollution propelled by the procedure.

This paper is focused on initiatives carried out by researchers which are relevant to environmental aspects thereafter predicting EDM performance by using machinability improvement techniques. The specific topic now foresees work carried out by researchers and aftermath of research.

Figure 2. Advantages of dry electro discharge machining (Skrabalak & Kozak, 2010).

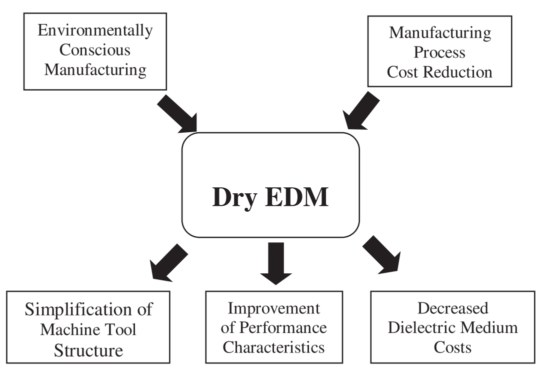
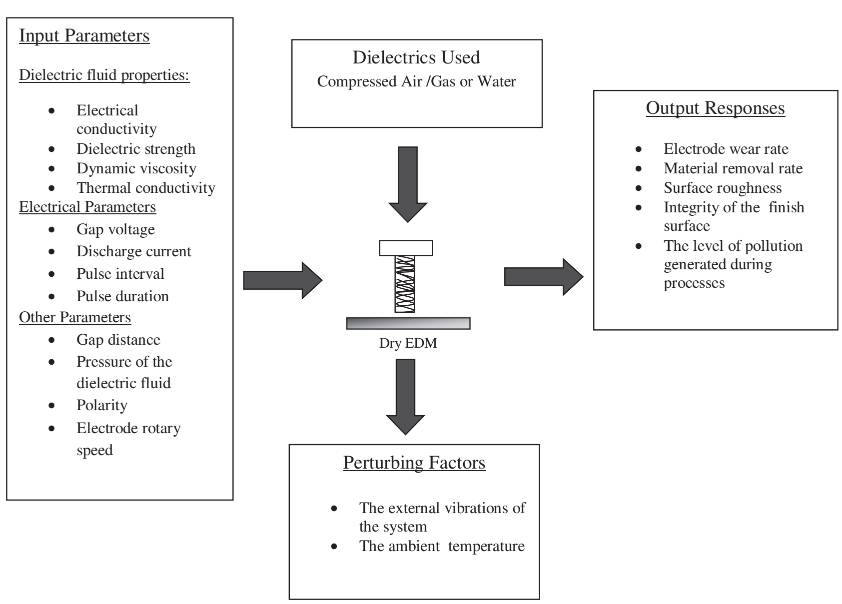


Figure 3. Factors for systemic analysis of the Dry EDM process (Besliu & Coteata, 2009).



Development in environment friendly EDM is presented in following divisions based on the (i) Material removal rate and Tool wear rate (ii) Out of roundness and Surface finish (iii) Surface integrity and (iv) Breakthrough techniques.

2.1. Performance assessment of green EDM machining considering material removal rate and tool wear rate as output responses

The noteworthy performance measures in EDM operation is material removal rate (MRR) and tool wear rate (TWR). Many researchers proposed different approaches to improve EDM performance. Various researchers explored innovative techniques to enhance MRR. However, in majority of research publications, it had been ascertained that researchers were solely inquisitive about finding the optimum process condition for output responses by considering different electrodes materials or kind of dielectrics used. After going through extensive literature review, it is felt to summarize the vital outcomes explored by the researchers that improved the process performance and its sustainability.

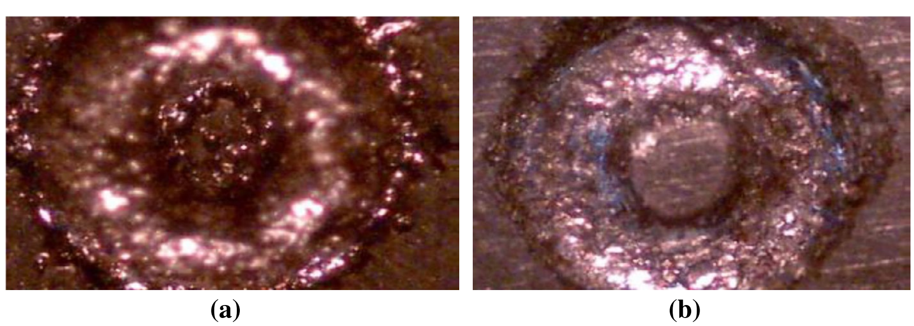
Kunieda et al. (1991) demonstrated new machining method to enhance the EDM performance by supplying oxygen gas in discharge gap. It was found that material removal got increased due to the oxidation reaction which increased the discharge energy and caused an enlarged discharge crater. Further, Kunieda and Yoshida (1997) notice that the removal of molten and evaporated work piece material gets increased by using compressed gas flow through a pipe tool electrode. The removed material solidified and did not remain attached along the surface of the work piece as well as on tool electrode, because application of the compressed gas flows. In another investigation, Yoshida and Kunieda (1999) studied tool wear in dry EDM and were on view that TWR was very negligible for most of pulse duration. This was only because of molten work piece material deposited on tool surface and protects tool against the excess wear. Zhanbo et al. (2005) in their investigation analyzed the influence of process factors and the possibility of 3D surface machining in dry EDM. They found that tool wear increased slightly as the rotational speed increased. They observed that optimum combination between depths of cut and gas pressure resulted in the maximum MRR and the least tool wear when pulse duration was kept to 25 μs. Yu, Jun, and Masanori. (2004) investigated the effectiveness of the dry EDM method in the machining of cemented carbide. Gaseous oxygen with high velocity was used as the dielectric medium during the experiment. Further, they compared the dry EDM performance to oil EDM and oil EDM milling. Their finding revealed that dry EDM-milling produced the smallest deviation due to very low electrode wear ratio. They also observed that the machining speed in dry EDM was higher than that of oil milling EDM but lower than the oil die-sinking EDM. In their exploration, Zhang, Zhang, Deng, Qin, and Niu (2002) stated that efficiency of EDM increases when an ultrasonic vibration in gas medium is used. They observed that, amplitude of ultrasonic actuation, discharge current, pulse duration, and open voltage, were some of the significant factors for increasing the MRR. Beşliu et al. (2010) used liquid and the compressed air as a dielectric to improve the EDM performance. Their findings suggested that electrode wear is lower in proposed process than that of wet EDM for a particular operating condition. Saha and Choudhury (2009) studied dry EDM and performed parametric analysis with rotary tubular electrode. Experiments were conducted by utilizing air as dielectric. Spindle speed, air pressure, discharges current, duty cycle, gap voltage, and pulses on time were the controllable process variables. Results show that current, duty factor, air pressure, spindle speeds were the significant factor effecting MRR. Moreover, TWR was kept as an independent operation parameter and was increased slightly. Xu, Zhang, Li, and Zhang (2009) studied, EDM machining of the cemented carbides with ultrasonic vibration assisted tool in gas medium. They suggested that by applying ultrasonic vibration, MRR increased appreciably. They further observed that in case of ultrasonic vibration assisted machining for a particular discharge current and pulse-on time, MRR gets substantially higher when compared to conventional dry EDM process. Govindan and Joshi (2011) used electrodes with peripheral slots for efficient debris disposal and to improve the MRR. They observed that peripheral slots accommodate more space for the flow of dielectric fluid hence, improving the flushing action. Further, analysis of the results indicated that discharge current, gap voltage, rotational speed and pulse-off time were the significant factors affecting the MRR in the dry EDM process. In addition, slotted electrodes significantly reduced the attachment of debris particles on the electrodes and reduced the electrode wear rate. Kunieda, Takaya, and Nakano (2004) tried to improve dry EDM machining performance by controlling the gap distance and by using the piezoelectric actuators. They used a simulator to study the effects of piezoelectric actuator on MRR and machining stability. Roth, Kuster, and Wegener (2013) analyzed the influence of different gases as dielectric on the sustainability of dry EDM process. It was suggested that the MRR was minutely affected by the high temperature, from the oxidation and that the main difference between oxygen and less oxidizing gases was to come up in different stability and time efficiency of the operation. Roth, Balzer, Kuster, and Wegener (2012) studied the MRR and breakdown behavior of the process for different tool and workpiece material. They suggested that the discharge behavior had a prerogative on the MRR of the workpiece. Govindan and Joshi (2010) investigated the effect of single discharge, dry electrical discharge drilling on MRR. They observed that the MRR is significantly influenced by discharge current, gap voltage and rotational speed. In most of the experiments, TWR was found to be almost zero. Further, they analyzed the wear characteristic of a single discharge for both dry EDM and conventional liquid dielectric EDM process as well. The outcome indicated that larger MRR and crater radius is obtained at low discharge energies, for a single discharge in dry EDM as compared to that of conventional EDM.

2.2. Performance assessment of green EDM machining considering out of roundness and surface finish

Surface finish affects the quality of an electric discharge machined part. Further, productivity is not only a matter of prime concern with a high level of accuracy for any process; but also it is a driving force of economic growth of any industry. Thus, it is invariably fascinating to have machining with high dimensional accuracy, in conjunction with better surface finish.

Furthermore, Li, Zhao, Wang, Kou, and Li (2004) suggested that to constrain discharge points dissipate in a gap, fixed gas pressure is prerequisite to consolidate deionization in dry EDM. To confirm the machining process steadfast at the spark discharge state. It was recommended that positive polarity to be used in dry EDM, since electrodes plays prominent roles in collision and ionization. Further in this line, Zhang, Du, Zhang, and Zhang (2006) used ultrasonic actuation to improve the efficiency of EDM in gas medium. The experimental results indicated that, the surface roughness increased with the rise of the open voltage, the pulse duration and the discharge current. In other investigation, Xu et al. (2009) performed experiments to develop a model, in order to evaluate finish of the machined surface. Finding suggested that roughness of machined surface increases with rise of gap voltage, pulse duration and discharge current. Curodeau, Richard, and Frohn-Villeneuve (2004) performed automated polishing of tool cavity using thermoplastic electrode and air as dielectric. Results showed that surface finish improved significantly with respect to conventionally used electrodes. Beşliu et al. (2010) studied dry EDM and found that the errors of the circular shape cross-section might be reduced by rotation of the electrode tool. During experimentation liquid and the compressed air were used as working fluids. Results as shown in Figure 4 indicated that for particular parametric combinations, the quality of the surface was better when air is used as a working fluid.

Figure 4. (a) Hole obtained using the liquid as dielectric and (b) Hole obtained using air as dielectric (Ramani & Cassidenti, 1985).



2.3. Green machining with surface integrity improvement techniques

In EDM operation surface of the workpiece are subjected to intense heat and rapid cooling provided by spark heat and dielectric flow. Differential heating and cooling induces residual tensile stress. During EDM, the crack formations on work surface start as the magnitude of thermal stresses surpass the fracture strength of the workpiece. It is obvious that, surface integrity affect the quality of an electric discharge machined component. Therefore, it is always desirable to have surface integrity better in machining.

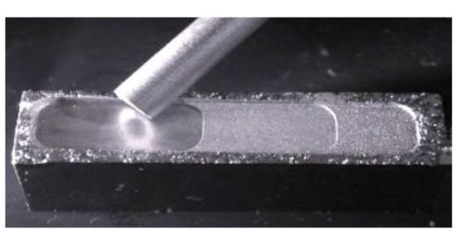
Umbrello (2012) performed experiments to analyze formations of recast layers, in machining of die steel using dry and cryogenic dielectrics. It was found that recast layer formation might be reduced or eliminated for a certain parametric combination and by using cryogenic liquid as a dielectric. Further in this line, Govindan and Joshi (2012) presented an analysis of formation of micro-cracks on the machined surfaces in dry EDM process and investigated the effect of process parameters on crack formation by scanning electron microscopy (SEM). It was suggested that the micro-crack formation can be best interpreted in terms of average crack length. Analysis of the results showed that, electrode rotation speed, discharge current, gap voltage and pulse off-time significantly affected the average crack length in both wall and bottom of the machined hole. A comparison of crack formation with the liquid dielectric EDM showed that the density of micro-cracks and average lengths were lower during dry EDM. Besliu and Coteata (2009) presented the results of simulation and mathematical modeling of the MRR and recast layer formation of electro discharge milling process with compressed air as dielectric. Observation was made that in case of DEDM milling, the problem of particles attaching the electrode surface was negligible, as the evacuation of the eroded particles from the working gap was relatively high. It was also suggested that, in case of machining at the micro-scale, DEDM milling process is more useful than EDM milling in kerosene, since electrode wear ratio was more precise in case DEDM milling process.

2.4 Green manufacturing innovative approaches to improve the machining performance

Despite several advantages of dry EDM process, it's one of the major limitation is low material removal ability in respect of conventional die sinking EDM process. For enhancing the performance of dry EDM operation many researchers have proposed a different approaches (Fujiki, Kim, Ni, & Shih, 2011; Gholipoor, Baseri, & Shabgard, 2015; Jahan, Malshe, & Rajurkar, 2012; Jahan, Virwani, Rajurkar, & Malshe, 2013; Jia, Kim, Hu, & Ni, 2009; Kao, Tao, & Shih, 2007; Liqing & Yingjie, 2013; Liquing, Fu, & Song, 2011; Masahiro & Shih, 2011; Tao, Shih, & Ni, 2008a, 2008b), in dry EDM like high-speed dry EDM milling, near dry EDM milling, magnetic assisted dry EDM, five-axis milling using near-dry EDM, cryogenic assisted dry EDM, nano-scale dry EDM and powder mixed nano-dry EDM.

Jia et al. (2009) studied the near-dry milling EDM for the post-processing operation of the satellite alloys. Findings showed that the machining performance was significantly affected by discharge current rather than the other process parameters. Kao et al. (2007) investigated the near dry EDM process using a mixture of water and air as the dielectric medium. They noted that at low discharge energy near dry EDM has a higher MRR and brings forth a smaller gap distance as compared to wet EDM. They proposed a mathematical model to establish the relationship between dielectric strength of water–air mixture and viscosity to the gap distance. Tao et al. (2008a) investigated a near-dry EDM milling method to get a mirror-like surface finish. In this method, they had used liquid-gas mist as the dielectric, delivered through a rotating tubular electrode. Result revealed that at the low discharge energy input, near-dry EDM exhibits good machining stability and smooth surface finish. They observed that the surface finish was expected to be further improved in near-dry EDM by reducing, the pulse duration. The proposed process produced mirror like surface finish as illustrated in Figure 5.

Figure 5. Illustration of the mirror-like machined surface (Tao et al., 2008a).

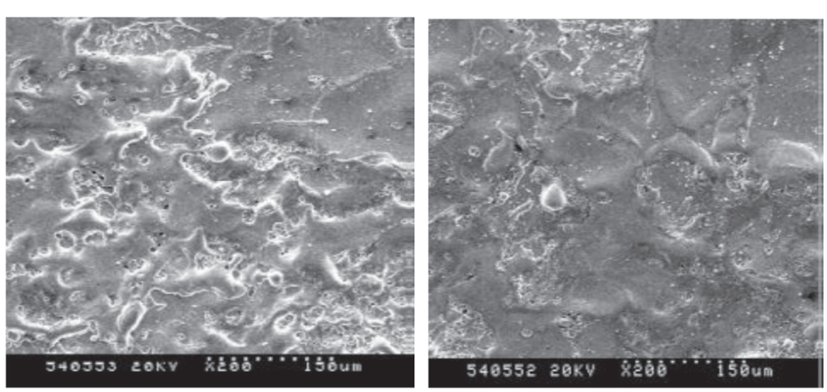


In this line of exploration, Tao et al. (2008b) investigated the dry and near-dry EDM milling for roughing and finishing operations without sacrificing MRR. To obtain high MRR, oxygen and copper electrode was selected during dry EDM and in case of near-dry EDM nitrogen-water mixture and graphite electrode was selected to obtained fine surface finish. Near-dry EDM exhibits the advantage of good machining stability and surface finish at low discharge energy input. To improve the surface finish in near-dry EDM, low pulse duration and low discharge current were identified as the key factors. In recent past, Gholipoor et al. (2015) performed comparative study of dry, near dry and wet EDM in drilling of die-steel. Their observation suggested that oil based EDM had high MRR, TWR and surface roughness at high discharge energy. Moreover, at low discharge energy near-dry EDM exhibited better MRR and less surface roughness. Further, SEM analysis reveals that specimen machined by near-dry EDM process had better surface integrity than the other processes used.

Joshi, Govindan, Malshe, and Rajurkar (2011) proposed a novel hybrid dry EDM for improving process performance. The process was implemented in a pulsating magnetic field. They found that the application of the magnetic field induces extra heat to the workpiece; hence, MRR in dry EDM can be improved considerably. Results stated that application of magnetic field causes an increment in MRR by 130% and tool wear was found to be almost negligible in comparison of dry EDM process without the magnetic assistance. They used SEM to illustrate improvements in surface quality of machined components. Further in this line of investigation, Teimouri and Baseri (2013) studied the dry EDM process assisted with ultrasonic actuation of specimen and magnetic field rotation. They used eccentric hole rotary brass tool to perform the experiments. Further, they analysed the effect of air injection pressure, tool speed, pulse current, pulse on time and pulse off time, on process responses namely MRR, SR, EWR and over cut. Findings suggested that rotation of magnetic field and simultaneously ultrasonic actuation of specimen improved the MRR and SR in comparison of conventional EDM process. Fujiki et al. (2011) put forward a new gap control approach for five-axis milling, using near-dry EDM process. This new gap controller enabled the electrode to be retracted in the way of its orientation and caused a faster recovery of average gap voltage due to widening of the discharge gap. When electrode retracted in its axial direction, EDM performance improved significantly. Although at that point there was no improvement in the TWR and surface roughness, but MRR increased by 30%. Further Masahiro and Shih (2011) proposed another method to prevent leakage of dielectric mist from the tubular electrode. The proposed approach was different from the conventional end milling process in material removal mechanism. Relations for tool positions and orientations to engage the electrode into the workpiece, machining of workpiece edge, smallest lead angle to machine a curved surface and minimum and maximum path interval to prevent the mist leakage from tubular electrode were derived. In addition it was discovered that, tool wear and crowning of electrode tip, caused difficulty in accurate minimum path interval which will cause the mist leakage.

Liqing and Yingjie (2013) proposed two new dry EDM techniques, namely oxygen-mixed dry EDM and dry EDM with cryogenically cooled workpiece, with the aim to increase MRR and improving the

Figure 6. Surface topography comparison of uncooled and cooled workpiece (Jahan et al., 2013).



(a) Uncooled (b) Cooled

surface integrity. The results show an enhancement in the MRR for both the oxygen-mixed EDM and the cryogenically cooled workpiece EDM. Further they found that surface roughness was less in case of cryogenically cooled workpiece (refer Figure 6). However, oxygen-mixed air achieved a higher MRR and that MRR increased with oxygen content in a two-gas mixing. Dry EDM with cryogenically cooled workpiece also recorded improvement in both the MRR and SR at the chosen experimental conditions. The MRR was improved about 30–50%, and SR was reduced by 10%, over what could be achieved with uncooled tool electrode. An enhanced ejection of debris in this approach was attributed as the main reason for the improvements over uncooled EDM experiments.

Jahan et al. (2012) performed an experimental investigation and delineation of a novel technique for nano-scale electro-machining (EM) in atmospheric air, named as dry nano-EM, by using scanning tunneling microscopy (STM) as the platform for nano-machining. Findings revealed that field induced evaporation due to intense heat generated at the gap width was the primary reason of material removal in dry nano-EM. The experimental results proved that dry nano-EM is capable of creating consistent nano-features with good repeatability and the magnitude of material removal increased almost linearly with increasing number of features machined and machining time, indicating the consistency in the proportions of the nano-features. Further, Jahan et al. (2013) introduced a comparative work between the wet and dry nano-EM processes based on process mechanism, machining performance, consistency and dimensional accuracy of the processes. The differences of two processes had also been discovered in the machining operation, proportions of the machined features and repeatability of the nano scale machined features. The self-tip-sharpening process with the continuation of machining had added several advantages to dry nano-EM over wet nano-EM in terms of dimensional accuracy of the nano scale features, repeatability and machining performance. In recent past, Bai, Zhang, Yang, and Zhang (2013) proposed novel powder mixed nano-dry EDM method to improve MRR effectiveness. Outcomes showed that proposed process improved the MRR under certain parametric operating condition. They suggested that, factors like tool rotation, flow rate, pulse duration, and peak current had a significant effect on MRR.

3. Green EDM machining with water based dielectric

In order to endorse green EDM process water is employed as an alternative dielectric to replace hydrocarbon oil in die sinking EDM process. The technologies of dry EDM and die sinking EDM with water as dielectric are at infancy stage. Moreover, stringent environmental obligations are imposed on machining sector to meet the green manufacturing with EDM process in near future. Comprehensive explorations of the published research paper on the role of water-based dielectrics for the last 30 years are discussed in the next sections.

3.1. Effect of water based dielectric on machinability

The MRR and electrode wear is less in case of water as dielectric in comparison of hydrocarbon oil as a dielectric in die sinking EDM. However, in some special cases like when brass electrode was used at negative polarity, application of deionized water as dielectric might be resulted in increased levels of MRR. Erden and Tramel (1981) investigated the EDM of steel in deionized water using brass electrode at negative polarity. They observed that for same operating conditions, EDM in deionised water produced increased MRR and less TWR in comparison of EDM with hydrocarbon oil. Jeswani (1981) investigated the machinability of EDM using kerosene and distilled water as dielectric medium. Their finding suggested that when high pulse energy was used machining in distilled water resulted in a lower tool wear and a higher MRR than in kerosene oil. It was likewise noted that with distilled water surface finish was better, although the machining accuracy was poor. Jilani and Pandey (Jilani & Pandey, 1984) reported that with the tap water superlative machining rates may be obtained and almost zero TWR may be achieved when copper tools with negative polarities was used while machining in water. They suggested that for certain pulse duration (pulse on time lower than 50μs) use of tap water as dielectric could produce better surface finish than distilled water and hydrocarbon oil.

In order to raise the effectiveness of deionized water some authors suggested to mixed organic compounds such as ethylene glycol, glycerin, polyethylene glycol 200, polyethylene glycol 400, polyethylene glycol 600, dextrose and sucrose in deionized water. Koenig and Joerres (1987) found that when EDM operation was performed with concentrated aqueous glycerin solution under specific parametric condition such as high discharge currents, large pulse on time and high duty cycle, machining performance was far better in comparison of EDM with hydrocarbon dielectrics. Highly concentrated aqueous glycerin solution with graphite electrodes when compared with hydrocarbon oil was found to be higher material removal (40%) and lower tool wear (90%). Koenig and Siebers (1993) reported that working medium had a considerable significance on the material removal mechanism. Under critical conditions, the spark eroding process in which water was used as dielectric medium had a better MRR. This was probably due to higher thermal stability and higher power allowing ability of water. Koenig et al. (1995) most recently reported that for roughing and finishing machining operations glycerin (50–60%) with water was suitable for machining of large areas such as forging dies and an enhancement in the MRR, about 100% can be accomplished. Masuzawa (1981), Masuzawa, Tanaka, and Nakamura (1983) have reported that for a better MRR, dielectric containing an organic compound of larger molecular weights can be preferred. Results suggested the possibility of advanced inflammable dielectric for EDM by introducing an organic solution in water. Machining characteristics of polyethylene glycol with water was found to be at par with conventional EDM oil. Zhang et al. (2013) used an oxygen-mixed water in oil emulsion as the dielectric in die-sinking EDM. Results showed that by mixing oxygen into the water in oil emulsion the MRR improved notably and the EWR reduced significantly. It was believed that with this oxygen-assisted machining method, recast layer produced was much finer. Further, Liu et al. (2013) proposed water in oil emulsion as the operating dielectric medium. Their finding suggested that performance of EDM process was significantly influenced by the content of water emulsion and discharge current. It was noted that both MRR and EWR decreased with rise in temperature of the water emulsion. Results suggested that water in oil emulsion can be used as the working fluid of the sinking EDM and reduced the environmental impact of the operation. Medellin, de Lange, Morales, and Flores (2009) performed experiment using different types of water dielectrics such as deionized water, tap water and mixtures of tap and deionized water to test the machinability of EDM operation. The results showed with water as dielectric (75% tap water and 25% deionized water) one could achieve, the maximum MRR and less TWR. However, inferior out of roundness was recited when deionized water was used as the dielectric.

For economic and ecological prospective commercial water-based, fluids like Elbolub, Vitol QL and Ionorex 500 plus are to be used for the production of moulds and dies. Dunnebacke (1992) reported that in roughing operations, MRR achieved with Elbolub has been 2–3 times higher than what could be achieved with hydrocarbon oil. It was also reported that for graphite electrodes using Elbolub as the dielectric, MRR was high, but had higher tool wear than that seen while machining with oil. Dewes, Aspinwall, Burrows, Paul, and El-Menshawy (2001) investigated the operation of different dielectrics on the EDM of Inconel 718 and reported that deionised water had the lowest MRR. Ionorex and BP180 led to similar removal rate, but BP180 had a higher value of relative electrode wear. Karasawa and Kunieda (1990) investigated the EDM in water based dielectric medium. Further, they studied the effect of different flushing action such as side jet flushing, suction flushing and pressure flushing on EDM responses. It was observed that MRR obtained with the side jet was 20% higher than pressure flushing due to better flushing conditions in the first case. Syed and Palaniyandi (2012) studied the effect of aluminum powder suspension in distilled water and finding suggested that MRR as well as TWR increased with increase in the concentration of aluminum powder. Moreover, this process had a high MRR and low TWR in comparison of conventional die sinking EDM.

3.2. Influence of water based dielectric on surface integrity

Appearance and surface roughness of the machined workpiece with water-based dielectrics and hydrocarbon oil are rather dissimilar. The surface of workpiece machined in the deionised water usually have oxides layers and higher values of surface roughness while surface of specimen machined in hydrocarbon dielectric have a contaminated appearance with carbon atoms inside the craters (Jeswani, 1981; Koenig & Siebers, 1993; Liu et al. 2013).

Pillans, Evensen, Taylor, and Eubank (2002) reported that rapid heating and cooling during EDM process causes metallurgical and mechanical properties alterations of the workpiece. It was observed that there are two distinct layers, the white or recast layer and the heat-affected zone on the surface of the workpiece machined by the EDM (Mc Geough, 1988). The formation of the recast layers are affected by the nature of the dielectric selected for the same. Further, it was observed that alteration of properties was due to the different chemical compositions and thermal conductivities of water and hydrocarbon based dielectric. Kruth, Stevens, Froyen, Lauwers, and Leuven (1995) performed comparative study of EDM with water and oil as different dielectric. It was reported that the carbon content of the recast layers of steel specimen was more than the base material when hydrocarbon oil was used as a dielectric while; carbon content decreased when deionised water was used as a dielectric medium. Ogata and Mukoyama (1993) found that carburization occurred in the recast layer of the workpiece when it was machined using conventional hydrocarbon oil and decarburization of the recast layer took place when workpiece was machined with deionised water. Regions of carburization were due to the thermal decay of the carbon present in hydrocarbon oil, resulting in a higher concentration of carbon along the surface of the recast layer. Decarburization occurred, when the carbon percentage of the recast layer decreased. The mechanism of decarburization was associated with the chemical reaction between carbon released from machined specimen, hydrogen and oxygen content of the deionised water. While, Chen, Yan, and Huang (1999) stated that when the workpiece is machined using deionised water, a bigger number of gaps along the blank layer is observed. Findings suggested that, presence of micro-cracks in the white layer reduced the fatigue strength of the machined components. Kranz et al. (1989) performed experimental investigations using hydrocarbon oil and water-based dielectric on different steels used as tool to study the relation between the micro-structure and hardness of machined workpiece. Results suggested that high-strength steels when machined with water-based dielectrics, micro-structure combined with cracks, caused a loss of toughness, while machining low-strength steels no such phenomena is observed.

With reference to the thermal decay of the hydrocarbon oil, the EDM operation release gases and exhaust. It was observed that deionised water generates the lowest measure of harmful substances, although benzopyrene and benzene are considered as carcinogenic (Evertz et al., 2001). Still, few researchers (Bommeli, 1983; Evertz et al., 2001) suggested that concentrations of both chemicals are more down to the maximum allowable value which is less hazardous to the operator and to the environment. In the recent past, Tang and Du (2014) used tap water as working fluid while EDM of Ti–6Al–4V alloy. They considered tap water as a dielectric, since it does not release gases that can harm the operator and pollute the environment. EWR, MRR and SR were selected as the objective parameters to evaluate the EDM performance. Their finding reveal that using green EDM technique machining of Ti6Al4V workpiece in tap water as dielectric can improve the MRR, reduced the operating cost and it is environment amiable in comparison of conventional EDM.

5. Conclusions and future scope

Thus, it can be concluded that to meet the stringent environmental obligations on machining sector and to meet the green manufacturing with EDM process the research till date is still in its infancy. The future work can be presented, based on the following conclusions drawn from the present literature review:

- Most of the published work focuses on electrode wear rate, material removal rate and surface finish. Further study should concentrate more on developing dry EDM as a precision machining operation. For which, along with electrode wear rate, material removal rate and surface finish other performance variables such as over-cut, process repeatability should also be considered.
- In most of the dry-EDM process, either air or oxygen is used as a dielectric. Further work may explore the use of nitrogen and inert gases as a dielectric. Nitrogen might be helpful if surface treatments such as nitriding are required as post-machining. However, helium due to its relatively very high heat capacity may offer better performance in terms of precision of the cut.

- Very few works are reported in terms of applications of dry EDM process in micromachining. Apart from drilling deep holes by DEDM in macro-scales, further research work is necessary at the micro-level to make dry electric discharge micro-machining possible.
- The development of dry and near-dry EDM technique focused much on to improve the MRR since MRR is lower than that of traditional EDM machining. Very few studies reported surface integrity of machined parts. In summation, analysis and quantification of other features on dry EDMed surfaces such as porosities, dimples and analytical modeling of the phenomenon of crack formation on dry EDMed surfaces needed to be taken as a fruitful future work.
- Current work in EDM is deficient relative to the theoretical modeling and process simulation, such as finite element analysis in dry EDM. In order to analyze the effect of the gaseous dielectric, existing oil EDM theory and simulation models may be modified. From literature review it was observed that till date, very few or no work is reported on modeling and optimization using hybrid approach during dry EDM machining.
- To study the nature of fluid dynamics of the dielectric gas flow in the inter-electrode gap and its effect on the performance of the process, further work is required in this regard.
- Under specific machining conditions, a mixture of gas and organic deionized water may cause higher material removal rate than hydrocarbon oil. This particular approach needs further investigations before its commercial use.
- Most of literature reported, used rotary tubular tool electrode. Very few works have been reported on the use of multi hole tool electrode. The effectiveness of green EDM process can be enhanced by the use of gas assisted multi hole or perforated rotary tool electrode.

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Author details
Nishant K. Singh[1]
E-mail: nishant.singh78@gmail.com
Pulak M. Pandey[3]
E-mail: pulakmohan@gmail.com
K.K. Singh[2]
E-mail: kks.composite@gmail.com
Manish K. Sharma[1]
E-mail: manish.kr009@gmail.com
[1] Department of Mechanical Engineering, Hindustan College of Science and Technology, Mathura, India.
[2] Department of Mechanical Engineering, Indian School of Mines, Dhanbad, India.
[3] Department of Mechanical Engineering, Indian Institute of Technology, Delhi, India.

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