Performance Analysis and Recent Study of Powder Mixed EDM and Powder Mixed Wire-EDM –A Review

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Abstract

Machinability is the term associated with easy cutting action,in which a metal can be machined, permitting the material removal with the desired surface finish at a lower cost. Working material with good machinability means the unwanted material can be removed quicklyagainst relatively small consumed power with reasonably good surface finish against low tool wear rate—various engineering materials having different machinability under the specific condition of machining. Variation of factors for determining machinability of the particular material, like cutting force, power consumption, tool life rating, surface integrity, limiting rate of material removal, tool geometry with the material and stability of the machine tool. Thus, machinability is a relative term associated with many factors.In order to compare the relative machinability, the term machinability index needs to consider. However, the machinability of advancedmachining processes like Electric Discharge Machining (EDM) or Powder Mixed Electric Discharge Machining (PMEDM) is not exactly the same as the conventional machining process. The machinability of EDM or PMEDM depends on its degree of complexity and many factors. At the same time, three essential attributes of EDM machinability arematerial removal rate (MRR), tool wear rate(TWR)and the surface roughness(SR) of the machined part. So, the machinability of EDM or PMEDM has beenan interesting area of research in recent days. In the last decades, various researchers have focused their studies on PMEDM for its different advantages. The objective of the present work is to review multipletypes of research. In addition, to highlight and summarize the research works in a systematic order and hence, to find out the future scopes in this particular field. It will motivate the researchers for exploring their study in the considered arena.

Keywords: *EDM, Dielectric fluid, spark gap, electrode, PMEDM, WEDM.*

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1. Introduction

Electrical discharge machining (EDM) or is a non-conventional machining process in which there is no contact in between the tool and workpiece. It is used for machining materials that are difficult to machine through conventional machining due to high hardness and brittleness. The dimensional accuracy and shape complexity are also the prime requirements for the selection of the EDM process. Precise machining can be carried out on electrically conductive and semi-conductive materials using the EDM process. Among several techniques of non-conventional machining, the use of EDM is growing enormously due to its accurate machining capabilities in various domains.The machining performance in the context of machinability for EDM and PMEDM is a comparatively novel area of research. The machinability index is utilized for making a comparison of the machining performance of various engineering materials through the various cutting process. However, the machinability index in a contact type (intimate physical contact in between tool and workpiece) machining can be defined as follows[1]:

$$\text{Machinability Index (I)} = \frac{V_i}{V_s} \times 100\%$$

Where, V_i is the Cutting speed of metal under investigation during 20 minutes tool life. and V_s is the Cutting speed of standard steel with 20 minutes operation. It is customary to consider all parameters which evaluate the machinability or rather says relative machinability in contact type machining as follows:

- Tool life with the type of tool wear for crater wear, wear on flank etc.
- Size and shape, chip type, inclination towards burr, chip thickness ratio.
- Cutting forces in combination with associated power consumption.
- Chip removal rate with efficiency.
- Surface quality, surface finish in combination with characteristics of the machined surface.
- The temperature at cutting zones.

Therefore, the machinability of EDM or PMEDM isa challenging area of research in recent days and may be focused on this area for future scope.Conventional EDM dielectric without powder particle associated with low discharge energy along with small tool-workpiece gap leads to a problem in gap cleaning as well as enhancement of capacitive effects, which ultimately delays the discharge ignition. The introduction of powder particles like Si, Cr, Al, Graphite, Cu, Sic, Al_2O_3 etc. into suitable dielectric in a controlled manner improves polishing performance, compared to conventional EDM and wired EDM (WEDM), resulting in depletion of crater size, the thickness of white layer and surface irregularities.

Several researchers[2–14]have already tried to explain the material removal mechanism consisting of three interrelated phases as a breakdown of dielectric, discharge and erosion. The improved polishing phenomena against the influence of powder on PMEDM are assumed to be the performance evaluation of high MRR, reduced TWR and reasonably good surface quality. They suspended powder particles force to reduce the resistance of insulation of dielectric fluid, enhancing the spark gap remarkably. A strong electric field is being generated in between the workpiece and tool material while a suitable voltage is applied. This suspended powder particle acts as a conductor. Chain is formed at various locations under sparking zone for the presence of powder particles, which make a bridge in between tool electrode and workpiece. As a result of which, the voltage across the gap along with the insulating strength of dielectric decreased and subsequently, short-circuiting took place and hence accelerating the explosion process in between the spark gap. Because of the enhancement in the number of discharges per unit time, faster sparking takes place that may cause rapid erosion from the work surface. Simultaneously the control addition of powder particles increases the plasma channels for which electric density is reduced, and uniform distribution of sparking may be possible, resulting in uniform erosion on the workpiece surface and improved surface finish. A basic schematic illustration of EDM has been presented in Figure 1.

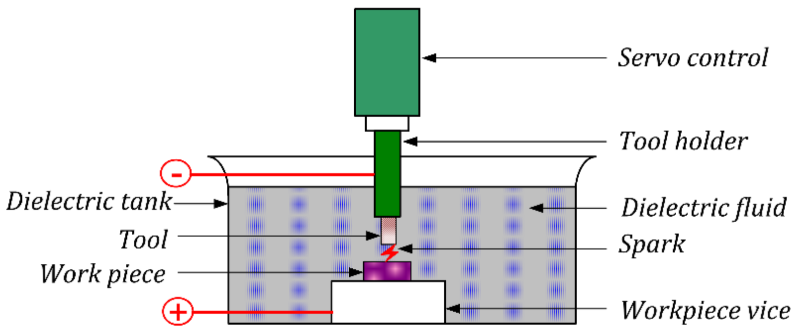

Fig. 1. Basic schematic illustration of EDM

The performance characteristics of machining through PMEDM depend upon the selection of input parameters. Process parameters can be classified into four types. The parameters for PMEDM are tabulated in Table 1.

Table 1: EDM process parameters [4,13–21]

Electric Parameters	***Non-Electric parameters***	***Electrode base Parameters***	***Powder based Parameters***
• Peak current • Discharge voltage • Pulse on time and Pulse of time. • Polarity • Electrode gap • Gap voltage • Duty factor • Polarity • Pulse frequency • Pulse waveform • Electric field intensity against applied voltage	• Shape and size of the dielectric tank • Die electric flushing • Electrode Rotating • the workpieces • Type of dielectric • Break down the strength of the dielectric • Flush point of the dielectric • Mixing efficiency of dielectric • Mixing time • Rotating the electrode	• Electrode material • Electrode size • Electrode Shape • Thermal conductivity of electrode material • Electrical conductivity of electrode material	• Powder type • Powder size • Powder shape • Powder itself • Powder conductivity • Powder concentration • Powder density

2. Literature review

The impact of PMEDM on the machining performance of EDM and WEDM isan exciting area of study. Research work of various researchers relevant to the above-mentioned topic are enumerated and stated in chronological order in the recent past, more than one and half decades as follows:

In the year 2003, EDM research by Ho and Newman[22].related to the improvement of performance measures, optimizing the process variables, monitoring and controlling the sparking process may be considered as an inception to the development of die-sinking EDM process. Schumacheret al.[23]interpreted the EDM process as an ion action which is identified as physical research of discharges in the air or in a vacuum in conjugation with investigations on the breakthrough strength of insulating hydrocarbon liquids. It is further added that the material removal reaction is grouped in an evaporation phase at the start of ignition and later in the ejection of fused material by instantaneous boiling at the discharge spots. The research work carried by Pauloet al. [24]reveals a very significant point in the field of PMEDM. The introduction of Si powder with variable concentration combined with dielectric fluid improves MRR, surface quality produced in the EDM process. Prakash et el.[25],in the year 2013, identified that PMEDM has a significant role on TWR. Jamadar et al.[26]in the year of 2014 investigated the influence of process parameters of EDM like (I_p), (T_{ON}), and Al powder concentration on machining performance of AISI-D3 die steel. Machining characteristics wereanalyzed in terms of MRR, TWR and SR value (R_a) of the AISI-D3 die steel. Saliya et al. [27]reviewed the influence of powder mixed dielectric on the performance of WEDM in the year 2014. Studies have been performed under variation of electrical parameters, and the effect of powder in dielectric on quality characteristics were reported in terms of surface finish, kerfs width in combination with machining time. Choudhary et al. [28]also reviewed current research trends and applications on (PM-EDM) in the same year. An experimental investigation was performed on EN-8 working material, processed by PMEDM into Kerosene dielectric fluid by Prajapati et al.[29]. Performance characteristics of AISI die steel was evaluated against variation of Cr powder concentration, I_P and T_{ON} by Abrol and Sharma [30].Mathapathiet al.[31]analysed the influence of Cr, graphite powder concentration, within Kerosene dielectric against I_P, T_{ON}, T_{OFF}, electrode lift time on MRR and tool electrode life through with SR and TWR. Kumaret al.[32]investigated the influence of Al and Si powder in distilled water on machining characteristics of Nimonic-90 through the WEDM process. A trial was made to find out the value of optimum process parameters such as I_P, T_{ON}, T_{OFF}, SV, WO in different dielectric conditions. Kumaret al.[33],in the year 2018, experimented with the performance of EDM process for machining Inconel 825 alloy through PMEDM process, using Al_2O_3 nano powder with deionized water. The experiment reveals that a maximum MRR of 47mg/min against a minimum Ra value of 1.487µm is obtained, which are 44% and 51% higher in comparison with the conventional EDM process.Sivakumar andBoopathi[34]performed an investigation with the machining of HSS-M2 tool steel material through WEDM using near dry(air-mist/oxygen-mist), replacing liquid dielectric which is considered as eco-friendly machining environment with cooling effect at cutting zone. Sivakumaret al.[35] identified various biomaterials for orthopaedic implant areas and other applications based on considering related metal toxicity, corrosion in the body and biocompatibility for living systems. They did further identify various tool electrodes and work piece (bio-implant) for machining through EDM and WEDM. Chakrabortyet al[36]. in the year of 2020 investigated the performance analysis of eco-friendly machining of Ti6Al4V using powder mixed with different dielectrics in WEDM. Fadhilet al. [37]in the year of 2020 investigated the effect of powder mixed dielectric on EDM process performance. Research reveals that maximum MRR (0.492g/min) is obtained at various process parameters as follows I_p is 24A,T_{ON} is100µs,C_P is 10g/l. Minimum TWR(0.00126g/min) is obtained against at various parameters values as follows I_P is10A, C_p is 10g/l. Better Ra (3.51 µm) against various process parameters I_p is 10A, T_{OFF} is 50 µs, C_P is 10g/l. Debnath et al. [14] studied the variation of response measures with the variation in the input parameters during electric discharge machining (EDM) of 430 stainless steel using brass tool. They usedtap water as the dielectric medium in this study.Baroi et al. [3] investigated the effect of input process parameters on the output parameters during electrical discharge machining (EDM) of titanium grade 2 alloy using deionized water as the dielectric medium.

The research progress inPMEDM during the review period and their significant findings are tabulated form in Table 2.

Table 2: Research carried out by the different researchers

Ref.	Author (Year)	Process parameters	Tool Electrode	Work piece material	Powder material used and dialectic	Findings / Outcome
[22]	Ho and Newman (2003)	Electrical and non-electrical parameters	NA	NA	NA	Classification of major EDM research areas and distribution of the collected EDM research publications.
[23]	Schumacher et al.(2004)	Electrical parameters	NA	NA	NA	Theory on practical EDM
[24]	Pecaset al. (2008)	Cp, flushing flow rate or dielectric flow rate over several electrode areas.	Cu, electrode area 1600 mm^2	Hardened mould steel AISI H13 (54 HRC) with EDM	Si powder with different concentration and dielectric used as Kerosene-Castrol SE fluid 180 flow rate 1l/min	Si powder concentration of 3g/l helps in the formation of little smoother craters resulting in relation to the SR. Due to conventional dielectric fluid, the abnormal discharges are independent of the flushing flow rate. As surface quality is a concern, there is a dielectric flow rate that minimizes the SR for each electrode area.
[38]	Jangra, K. et al (2011)	Three levels of I_p, T_{ON}, T_{OFF}, wire feed rate (WF)against constant SV(30V) and dielectric flow rate (DFR)	Zinc coated brass wire of diameter 0.25 mm	Tungsten carbide (13mm thick) composite(77HRC) with WEDM	Distilled water without powder is used as dielectric fluid with the range of dielectric flow rate as 0-10 LM^{-1}	The optimal value of $T_{OFF,}$ $I_{P,}$ T_{ON}, SV, wire tension, the flow rate for good cutting speed is 80A,122 µs,40 µs,40V,6N,7$LM^{-1,}$ respectively. With tapper angle 3º and for minimum SR the same will be 122A,108 µs,40V,8N,10LM^{-1}
[39]	Sivakumar and Boopathi(2012)	GV, Spark current, pulse width, pulse interval	Wire tool (99.95% pure) Mo tool steel diameter 0.18	HSS-M2 High speed steel (Work piece thicknes of 6 mm and length of	Without powder near dry dielectric fluid (Air-mist/Oxygen	Research in the field of emerging area near dry WEDM using air mist and oxygen-mist deionised water as dielectric fluid. Comparative study is made for oxygen-mist and air-mist near dry

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			mm with wire feed rate 250 rpm.	20 mm) with WEDM automatic fuzzy control CNC)	–mist with gas deionised water-based dielectric.	WEDM considering MRR along with Surface finish as output parameters. It is observed that MRR is 19.8% higher in case of oxegen-mist near dry WEDM than air-mist medium. But surface finish of the oxygen-mist medium has17.38% lower than air-mist near dry WEDM.
[25]	Prakashet al.(2013)	3 levels of peak current, 3 levels of T_{ON} and 3 levels of T_{OF}	Cu electrode	EN-31 die steel with PMEDM	Two powders to be suspended in the dielectric one by one graphite and Cu with kerosene as dielectric with EDM	PMEDM has significant influence on TWR. TWR is comparatively larger value with Cu additives and lower value while Graphite powder is used within dielectric. Due to increase in I_P and $_{TON}$ the TWR is also increase.
[26]	Jamadar et al.(2014)	I_P, T_{ON}, concentration of Al powder in the dielectric fluid and keeping constant polarity as straight polarity.	Round cylindrical Cu electrode (diameter 22 mm)	AISI D3 die steel with PMEDM	Al powder with IPOL oil as dielectric fluid.	All powder mix dielectric resulted in in high MRR, good surface finish when compared with pure dielectric. MRR & TWR both are apparently increased with the increase of I_P and T_{ON}. Maximum MRR is obtained at I_P=14A with T_{ON} as 150µs along with Al powder concentration of 6 g/l. Low TWR is achieved at I_P=2A, with T_{ON}=50µs against powder concentration of 6g/l. A stirring arrangement and side jet flushing system was employed for even, homogeneous power mix and for removing the debris from the spark gap. Low SR is achieved at I_P =2A with T_{ON}=150µs against powder concentration of 6g/l.

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[40]	Talla, G.et al.(2014)	Powder concentration (C_P) I_P T_{ON} and duty cycle (T_{au})	Cu electrode	Al-Al_2O_3 MMC (Metal Matrix Composite) With EDM	Al/Al_2o_3 MMC particle size 74 µm (200 mesh) with Kerosene as dielectric fluid.	Introduction of Al/Al_2o_3 powder in kerosene dielectricMRR increases, SR decreases. The recommended value of C_P=6g/l, I_P=3A, T_{ON}=150µs and T_{au}= 85% in case of PMEDM of Al/Al_2O_3 MMC.
[29]	Prajapati et al. (2014)	I_P, T_{ON}, T_{OFF}, C_P	Cu electrode (15 mm diameter)	EN-8(50 mm × 30 mm × 6 mm) with EDM	Sio_2 with 40µm particle size powder with kerosene as dielectric fluid.	Optimum value of various process parameters are as follows I_P =17A, C_P=6g/l, T_{ON}=50µs for maximum MRR.
[30]	Abrol and Sharma (2015)	I_P, T_{ON}, T_{OFF}, C_P	Cu electrode	AISI D2 die steel with PMEDM	Chromium powder of particle size (45-55 µm) with kerosene as dielectric fluid.	MRR is affected by I_P, T_{ON}, C_P. With increase of$I_P$andT_{ON}, MRR increases, however TWF decreases with the increase of Cr powder concentration. SR mainly affected by T_{OFF}.
[31]	Mathapathi et al. (2015)	I_P, T_{ON}, T_{OFF}, lift timeand C_P	Cu tool electrode with diameter of 20 mm	HCHCr die steel (dimension 900 mm× 650 mm×100mm) Hardness HRC 54-58 after treatment) with PMEDM	Chromium powder (15-20 µm) of particle size and graphite powder one at a time Al_2O_3 powder with kerosene as dielectric medium.	Mixing of powder with dielectric is responsible for increase of MRR compared to conventional EDM. MRR is influenced maximum by increase of I_P. MRR decreases while increasing of T_{OFF}. Tool Electrode lifts time increase, MRR increased.

[32]	Kumar et al. (2015)	T_{ON}, T_{OFF}, I_P, SV, WOagainst wire diameter of 250 µm with work piece height 12.5 mm against wire material copper coated brass.	Wire material copper coated brass.	Nimonic-90 with WEDM	Al and Si powder (mesh size 400) with distilled water dielectric having conductivity of 20 mho.	Mixing Al and Si powder separately with dielectric fluid, resulting in significant modification in surface texture and recast layer becomes smoother and denser which ultimately responsible for increase of micro hardness.
[33]	Kumar et al. (2018)	I_P, T_{ON}, gap voltage against constant process parameters as duty cycle, spark timing and bypass current.	Cu tool with cross section of 5 mm × 15 mm.	Super alloy Inconel 825 plate of 100 mm × 50 mm × 5mm, NPMEDM	Al_2O_3 nano powder of average particle size 45 nm mixed with demonized water as dielectric fluid (volumetric concentration of Al_2O_3 nano powder is 0.25%)	Research reveals that as I_P increased against constant T_{ON} and gap voltage, MRR also increased. When the value of T_{ON} increases, higher value of MRR is obtained. Addition of Al_2O_3 nano powder improves the surface topography of machined surface.
[41]	Modi et al. (2019)	I_P, T_{ON}, duty cycle against steady flow rate of dielectric fluid of 4 l/min	Bronze (diameter 10 mm)	Nimonic 80 A (20 mm diameter) machining through PMEDM	15-20 µm chromium and Aluminum powder (0.08-0.09 µm) one by one with dielectric of Kerosene oil is used.	The Size of Al powder has direct impact on MRR and SR.purpose behind Size range of 15-20 µm Al powder is the preferred size. Maximum MRR is obtained against powder size of 80-90nm and minimum MRR is obtained against the size range of 15-20 µm. Opposite pattern is observed for SR incase of PMEDM.

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[36]	Chakraborty et al. (2020)	T_{ON}, T_{OFF}, GV, fluid level.	Brass electrode of 0.25 mm diameter.	Ti6Al4V (size 200mm × 27 mm × 2.5 mm) with WEDM	(B4C with average grain size of 10 µm) with de-ionized water and kerosene used as dielectric	Output response of MRR and SR against four input parameters are studied. Higher MRR is obtained against increasing T_{ON} and T_{OFF} value of 6 µs provides best output. GV indirectly proportional to SR. The fluid level in the dielectric tank has impact on dielectric consumption in surfactant added PMWEDM. Against cost of production and safety operation in PMEDM HAZOP is considered to be a vital tool.
[37]	Fadhil et el. (2020)	I_P, T_{ON} and C_P	Cu electrode	M2 High speed steel (HSS) with PMEDM	Graphite and SiC powder particle size (1-2 µm) mixture of graphite –Si powder with transformer oil as dielectric	Maximum MRR was obtained 0.492 g/min against at a I_P =24A, T_{ON}= 100µs and $C_{P=}$ 10g/l. Minimum TWR was obtained at 0.00126 g/min at I_P =10A, T_{ON} =100 µs and C_P = 10 g/l. Ra=3.51 µm at I_P =10 A, T_{OFF}=50 µs C_P =10 g/l.
[42]	Sundriyal et al. (2021)	Diameter of tool, dielectric mist flow rate, concentration of metallic powder and mist pressure of dielectric fluid.	tool electrode material (copper) with different dimensions.	EN-31 with PMND-EDM.	mixture of EDM oil (LL-221), compressed air, metallic powder (zinc), and 5% glycerol serving as a stabilizing agent	Optimum process parameters for the experimental condition for maximum MRR (0.11 mg s^{-1}) was at tool diameter at A1 (2mm), flow rate of mist at B3 (15 ml min^{-1}), the concentration of metallic powder at C3 (25 gm l^{-1}) and mist pressure of dielectric at D3 (0.6 MPa). It has been also concluded that metallic powder was responsible for surface modification to achieve higher micro-hardness value up to 530.10 Vickers hardness number along with refined surface characteristics.

3. Conclusion

The extensive literature survey infers that technological advancement aids in real-time sensing and compensation of tool wear, which in turn helps in increasing the machining efficiency by saving time. Extensive literature review for more than last one and half decades in the field of PMEDM on machinability the proposed future scope of work may be identified as follows:

- The influence of dielectric fluid tank shape and size in combination with flushing arrangements along with powder particle need to be investigated.
- Considering eco-friendliness, near dry EDM and WEDM may be one of the challenging areas of future scope in view of working environment safety and health of the operator.
- Very little research has been carried out to date in the area of performance evaluation of various nano-powder mix dielectric for the EDM process.
- There are several research worksthat have already been carried out with the concentration of powder particles in the EDM and WEDM processes. But the influence of powder shape and size on EDM performance needs to be investigated thoroughly. So, these may be identified future scope for recent days.
- Hybrid machining with EDM and WEDM like ultrasonic-assisted PMEDM may be one of the examples of future research areas.
- The machinability of the contactless machining process needs to be studied thoroughly. Extensive experiments and investigations can only define the machinability index of various engineering materials. So, there is immense scope of research to study the machinability index of PMEDM in order to find out relative machining efficiency and hence may estimate machining time for various newly discovered engineering materials.
- Recent development in the field of material Science and technology gifted us extremely hard, newly discovered many metals matrix composite of low electrical conductivity. Machining such newly invented critically important engineering materials through PMEDM and PMWEDM may be the next challenge for manufacturing professionals. So, these may be identified as the future scope in the field of PMEDM.

References

[1] J.P. Kaushish, Manufacturing processes, 2nd ed., PHI Learning Pvt Ltd., Delhi, 2016.

[2] T. Debnath, P.K. Patowari, Concept development for fabricating threaded micro-pin using wire-EDM, J. Brazilian Soc. Mech. Sci. Eng. 41 (2019) 1–9. https://doi.org/10.1007/S40430-019-1916-3/FIGURES/6.

[3] B.K. Baroi, T. Debnath, Jagadish, P.K. Patowari, Machinability assessment of titanium grade 2 alloy using deionized water in EDM, Mater. Today Proc. 26 (2020) 2221–2225. https://doi.org/10.1016/J.MATPR.2020.02.482.

[4] A. Kumar, A. Mandal, & Amit, R. Dixit, & Deepak, K. Mandal, Quantitative analysis of bubble size and electrodes gap at

different dielectric conditions in powder mixed EDM process, Int. J. Adv. Manuf. Technol. 107 (2020). https://doi.org/10.1007/s00170-020-05189-x.

[5] Y.T. Yu, S.F. Hsieh, M.H. Lin, J.W. Huang, S.F. Ou, Effects of gas-assisted perforated electrode with rotation on the machining efficiency of PMEDM of titanium, Int. J. Adv. Manuf. Technol. 107 (2020) 1377–1386. https://doi.org/10.1007/S00170-019-04882-W.

[6] S. Deka, S. Kar, P.K. Patowari, Machinability of Silicon and German Silver in Micro Electrical Discharge Machining: a Comparative Study, Silicon. 13 (2021) 1065–1077. https://doi.org/10.1007/S12633-020-00496-0.

[7] C. Zhao, J. Ming, Q. Zhang, al -, X. Xiangyang, Z. Siqi, D. Peng -Recent citations, P. Jun Liew, C. Yee Yap, J. Wang, T. Zhou, J. Yan, F. Kejuruteraan Pembuatan, Surface modification and functionalization by electrical discharge coating: a comprehensive review, Int. J. Extrem. Manuf. 2 (2020) 012004. https://doi.org/10.1088/2631-7990/AB7332.

[8] A.K. Singh, P.K. Patowari, M. Chandrasekaran, Experimental study on drilling micro-hole through micro-EDM and optimization of multiple performance characteristics, J. Brazilian Soc. Mech. Sci. Eng. 42 (2020) 1–14. https://doi.org/10.1007/S40430-020-02595-W/FIGURES/10.

[9] A. Sarmah, S. Kar, P.K. Patowari, Surface modification of aluminum with green compact powder metallurgy Inconel-aluminum tool in EDM, Https://Doi.Org/10.1080/10426914.2020.1765253. 35 (2020) 1104–1112. https://doi.org/10.1080/10426914.2020.1765253.

[10] E.K. Mussada, P.K. Patowari, Development of intelligent system for predicting MTR in EDC process using powder metallurgical tools, Grey Syst. Theory Appl. 10 (2020) 321–337. https://doi.org/10.1108/GS-01-2020-0006.

[11] G. Pellegrini, C. Ravasio, A sustainability index for the micro-EDM drilling process, J. Clean. Prod. 247 (2020). https://doi.org/10.1016/J.JCLEPRO.2019.119136.

[12] P.P. Das, S. Chakraborty, Parametric analysis of a green electrical discharge machining process using DEMATEL and SIR methods, OPSEARCH. 57 (2020) 513–540. https://doi.org/10.1007/S12597-019-00410-2/TABLES/16.

[13] D. Kumar, N.K. Singh, V. Bajpai, Recent trends, opportunities and other aspects of micro-EDM for advanced manufacturing: a comprehensive review, J. Brazilian Soc. Mech. Sci. Eng. 42 (2020) 1–26. https://doi.org/10.1007/S40430-020-02296-4/TABLES/2.

[14] T. Debnath, B.K. Baroi, Jagadish, P.K. Patowari, Machinability study of 430 stainless steel using tap water in EDM, Mater. Today Proc. 26 (2020) 2179–2183. https://doi.org/10.1016/J.MATPR.2020.02.475.

[15] T. Debnath, P.K. Patowari, Fabrication of an array of micro-fins using Wire-EDM

and its parametric analysis, Mater. Manuf. Process. 34 (2019) 580–589. https://doi.org/10.1080/10426914.2019.1566959.

[16] G. Li, W. Natsu, Realization of micro EDM drilling with high machining speed and accuracy by using mist deionized water jet, Precis. Eng. 61 (2020) 136–146. https://doi.org/10.1016/J.PRECISIONENG.2019.09.016.

[17] H.A. Hegab, M.H. Gadallah, A.K. Esawi, Modeling and optimization of Electrical Discharge Machining (EDM) using statistical design, Manuf. Rev. 2 (2015) 21. https://doi.org/10.1051/MFREVIEW/2015023.

[18] S. Sundriyal, R.S. Walia, Vipin, Powder Mixed Near Dry Electric Discharge Machining Parameter Optimization for Tool Wear Rate, (2020) 3–16. https://doi.org/10.1007/978-981-32-9471-4_1.

[19] B. Singaravel, K. Chandra Shekar, G. Gowtham Reddy, S. Deva Prasad, Performance Analysis of Different Tool Shape in Electric Discharge Machining Process with Vegetable Oil as Dielectric Fluid, Lect. Notes Mech. Eng. (2020) 1069–1077. https://doi.org/10.1007/978-981-15-1201-8_114.

[20] B.P. Mishra, B.C. Routara, Evaluation of technical feasibility and environmental impact of Calophyllum Inophyllum (Polanga) oil based bio-dielectric fluid for green EDM, Measurement. 159 (2020) 107744. https://doi.org/10.1016/J.MEASUREMENT.2020.107744.

[21] S. Das, S. Paul, B. Doloi, Feasibility investigation of neem oil as a dielectric for electrical discharge machining, Int. J. Adv. Manuf. Technol. 106 (2020) 1179–1189. https://doi.org/10.1007/S00170-019-04736-5/TABLES/9.

[22] K.H. Ho, S.T. Newman, State of the art electrical discharge machining (EDM), Int. J. Mach. Tools Manuf. 43 (2003) 1287–1300. https://doi.org/10.1016/S0890-6955(03)00162-7.

[23] B.M. Schumacher, After 60 years of EDM the discharge process remains still disputed, J. Mater. Process. Technol. 149 (2004) 376–381. https://doi.org/10.1016/J.JMATPROTEC.2003.11.060.

[24] P. Peças, E. Henriques, Effect of the powder concentration and dielectric flow in the surface morphology in electrical discharge machining with powder-mixed dielectric (PMD-EDM), Int. J. Adv. Manuf. Technol. 37 (2007) 1120–1132. https://doi.org/10.1007/s00170-007-1061-5.

[25] V. Parkash, D. Kumar, Effect of Powder Mixed Dielectric Medium on Tool Wear Rate in EDM, Int. J. Sci. Res. 2 (2012) 107–109. https://doi.org/10.15373/22778179/FEB2013/38.

[26] M.M. Jamadar, M. V Kavade, Effect of Aluminium Powder Mixed EDM on Machining Characteristics of Die Steel (AISI D3), Int. J. Mech. Prod. Eng. (2014) 2320–2092.

[27] J. Saliya, Comparative Study for the effect of Powder mixed dielectric on

Performance of Wire EDM A Literature Review, Int. J. Eng. Dev. Res. 2 (2014).
[28] S.K. Choudhary, S.K. Choudhary, R.S. Jadoun, Current Research Issue, Trend & Applications of Powder Mixed Dielectric Electric Discharge Machining (PM-EDM): A Review, (n.d.).
[29] R.A. Prajapati, H. Patel, Experimental Investigation of Powder mix EDM using Silicon Dioxide as a Powder additive for Surface Roughness, Int. J. Adv. Eng. Res. Dev. 2 (2015).
[30] A. Abrol, S. Sharma, Effect of chromium powder mixed dielectric on performance characteristic of AISI D2 die steel using EDM, Int. J. Res. Eng. Technol. 4 (2015) 2321–7308.
[31] U. Mathapathi, Material removal rate with powder mixed Dielectric on Electric Discharge Machining, Int. J. Emerg. Technol. (Special Issue NCRIET-2015). 6 (2015) 274–283.
[32] V. Kumar, K.K. Jangra, V. Kumar, An experimental study on trim cutting operation using metal powder mixed dielectric in WEDM of Nimonic-90, Int. J. Ind. Eng. Comput. 7 (2016) 135–146. https://doi.org/10.5267/J.IJIEC.2015.7.002.
[33] A. Kumar, A. Mandal, A.R. Dixit, A.K. Das, Performance evaluation of Al2O3 nano powder mixed dielectric for electric discharge machining of Inconel 825, Https://Doi.Org/10.1080/10426914.2017.1376081. 33 (2017) 986–995. https://doi.org/10.1080/10426914.2017.1376081.
[34] K. Sivakumar, S. Boopathi, Experimental Comparative Study of Near-Dry Wire-Cut Electrical Discharge Machining (WEDM), Eur. J. Sci. Res. 75 (2012) 472–481.
[35] W.J.. J.. Sivakumar.S, Adamkhan.M, A Research on Machinability of Bio Implant by Electric Discharge Machining Process, Int. J. Recent Technol. Eng. 8 (2019) 260–263. https://doi.org/10.35940/ijrte.D1053.1284S219.
[36] S. Chakraborty, S. Mitra, D. Bose, Performance Analysis on Eco-friendly Machining of Ti6Al4V using Powder Mixed with Different Dielectrics in WEDM, Int. J. Automot. Mech. Eng. 17 (2020) 8128–8139. https://doi.org/10.15282/IJAME.17.3.2020.06.0610.
[37] S.R. Fadhil, S.H. Aghdeab, Effect of Powder-Mixed Dielectric on EDM Process Performance, Univ. Technol. 38 (2020) 1226–1235. https://doi.org/10.30684/ETJ.V38I8A.554.
[38] K. Jangra, S. Grover, A. Aggarwal, Machinability evaluation of tungsten carbide composite with wire EDM, Artic. J. Manuf. Technol. Res. 3 (2011) 91–107.
[39] M.A. Ansari, K.Y. Kim, K. Anwar, S.M. Kim, A novel passive micromixer based on unbalanced splits and collisions of fluid streams, J. Micromechanics Microengineering. 20 (2010) 055007. https://doi.org/10.1088/0960-1317/20/5/055007.

[40] G. Talla, S. Gangopadhyay, C.K. Biswas, Multi Response Optimization of Powder Mixed Electric Discharge Machining of Aluminum/Alumina Metal Matrix Composite Using Grey Relation Analysis, Procedia Mater. Sci. 5 (2014) 1633–1639. https://doi.org/10.1016/J.MSPRO.2014.07.351.

[41] M. Modi, G. Agarwal, Effect of aluminium and chromium powder mixed dielectric fluid on electrical discharge machining effectiveness, J. Home Apem-Journal.Org. 14 (2019) 323–332. https://doi.org/10.14743/apem2019.3.330.

[42] S. Sundriyal, R. Walia, Performance enhancements in powder-mixed near-dry electric discharge machining, Indian J. Eng. Mater. Sci. 28 (2021) 493–501.