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RESEARCH ARTICLE

INVESTIGATION OF THE EFFECT OF SILICON POWDER ON THE PERFORMANCE OF ELECTRIC DISCHARGE MACHINE

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ABSTRACT

Main purpose of this research to investigate the effect of silicon powder on material removal rate (MMR), tool wear rate (TWR) and surface roughnes (SR) on AISI D3 steel in powder mixed electronic discharge machining process (PMEDM). The results of the research could be applied in the production industries and even in small workshop having EDM machinies. This study was conducted by using EDM machine with a copper tool of 20mm dia, rectangular workpiece and silicon powder having grain size of 44micron. The controlled factors were the current, powder concentration, pulse on time and pulse off time. For this experiment, we used Taguchi design with L8 Orthogonal Array to have minimum reading and the result showed that addition of silicon powder in dielectric fluid increases MRR, TWR and SR. Furthermore, the powder concentration was influencing factor after current for material removal rate as for tool wear rate input current was the most influencing factor and in case of surface roughness the effect of powder concentration was minimum. The equation was used to obtain the optimum result and was further compared with the experimental result. The error obtained was under the specified value.

INTRODUCTION

Electrical Discharge Machining (EDM) is a thermoelectric process where erosion of workpiece material occurs by high frequency controlled pulses generated in the dielectric medium between the tool and workpiece electrodes separated by a small gap. The limitations of the process include low surface quality and poor material removal rate. A plasma channel is created due to the continuous bombardment of ions and electrons generating temperature in the range of 8000 °C–12000 °C in the discharge gap which causes vaporization and erosion of the material. Powder mixed electro-discharge machining (PMEDM) is a promising technique which overcomes the limitations and improves the machining capabilities of EDM. Addition of a fine conductive powder to the dielectric fluid decreases its insulating strength and consequently increases the inter-electrode space causing an easy removal of the debris. On application of a voltage of 80–315 V, an electric field in the range of 105– 107 V/m is formed, giving rise to positive and negative charges on the powdered particles. The powdered particles start moving in a zig-zag path on getting energized, thus forming clusters in the sparking area. The bridging effect takes place underneath the sparking area causing multiple discharges in a single pulse leading to quicker sparking and erosion from the workpiece surface. This easy short circuit enhances the machining rate of the process. The plasma channel gets widened and enlarged, producing steady and consistent sparks forming shallow craters on the workpiece surface with superior surface quality. Material removal occurs from both the electrode surfaces and under suitable machining conditions, the removed material combined with the powder particles get deposited on the surface of the workpiece, modifying and improving the properties resulting in breakdown of the dielectric fluid. As the sparking trend changes in the presence of abrasive powders, lot of alteration in the surface properties occurs. On the basis of the results discussed for temperature distribution in the PMEDM workpiece, the machining mechanism for PMEDM is proposed. A schematic diagram of the proposed mechanism of material removal in PMEDM is illustrated in Fig. 1.1. When a voltage of 80–320 V is applied to both the electrodes, an electric field in the range 105–107 V/m is created. The spark gap is filled up with additive particles and the gap distance between tool and the workpiece increases from. Schematic representation of machining mechanism of PMEDM. (a) It is expected that the insulating strength of the dielectric fluid decreases as powder is suspended into it.

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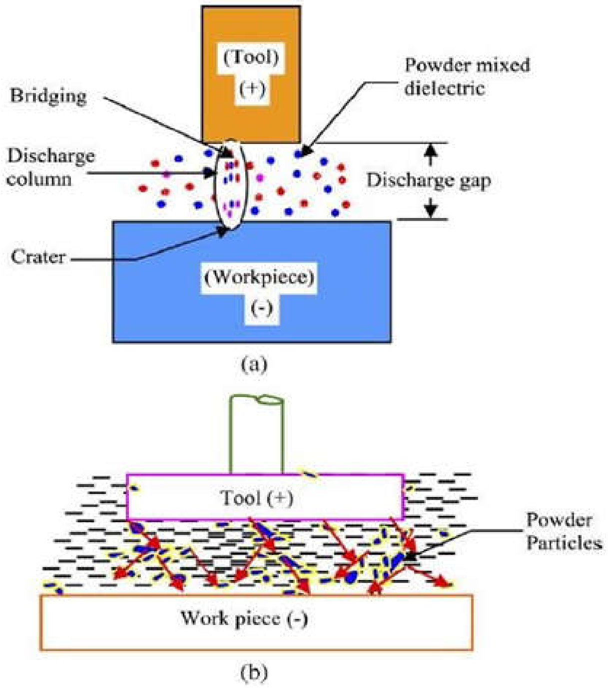

Fig. 1. Working principle of PMEDM

The spark gap distance is increased by many folds than normal EDM. It is proposed that the increase in gap might have caused wider discharge passages. (b) In a wider and enlarged plasma channel, the suspended powder particles share and redistribute the impact force. As a result, shallow, uniform and flat craters are formed on the workpiece surface. 25–50 μmto many times as shown in Fig.2.2. The powder particles get energized and behave in a zigzag fashion. The grains come close to each other under the sparking area and gather in clusters. Under the influence of electric forces, the powder particles arrange themselves in the form of chains at different places under the sparking area. The chain formation helps in bridging the gap between both the electrodes. Due to the bridging effect, the gap voltage and insulating strength of the dielectric fluid decrease. The easy short circuit takes place, which causes early explosion in the gap. As a result, the 'series discharge' starts under the electrode area. Due to increase in frequency of discharging, the faster sparking within a discharge takes place which causes faster erosion from the work piece surface. At the same time, the added powder modifies the plasma channel. The plasma channel becomes enlarged and widened. The electric density decreases; hence sparking is uniformly distributed among the powder particles. As a result, even and more uniform distribution of the discharge.

Literature Review

Gurule N. B and Nandurkar K. N, (2012), investigated the potential of PMEDM for enhancing material removal rate (MRR) of Die steel with rotary tool. Taguchi methodology has been adopted to plan and analyze the experimental results. Experimental results indicate that the current, on time, tool material, tool rpm and powder concentration significantly affect MRR. Dielectric- kerosene, powder- Aluminium, workpiece material- die steel D2. The maximum MRR is produced at 4 g/l of Al powder, 900 tool rpm with Cu tool. Khalid Hussain Syed and KuppanPalaniyandi, (2012), have done the experimental investigations on addition of aluminium metal powder to dielectric fluid in EDM. The present investigation uses distilled water mixed with aluminium powder as dielectric fluid. The workpiece and electrode materials chosen for the investigation were W300 die-steel and electrolytic copper, respectively. Taguchi design of experiments is used to conduct experiments by varying the parameters such as peak current, pulse on-time, concentration of the powder, and polarity. The process performance was measured in terms of material removal rate (MRR), electrode wear ratio (EWR), average surface roughness (Ra), and white layer thickness (WLT). The present work on addition of aluminium metal powder in distilled water resulted in high MRR, good surface finish, and minimum white layer thickness when compared with pure distilled water. Arya *et al.,* (2012), conducted the experiments (i.e. Machining) on Al/SiC metal matrix composite (MMC). Powder Mixed Electrical discharge machining (PMEDM) is used for machining of Al/SiC MMC. PMEDM is a technological improvement in conventional EDM, which was previously studied by many researchers to better MRR with good surface roughness (SR).

In this study, the controllable machining process parameters (i.e. Peak Current (Ip), Duty Cycle, Powder Concentration (PC), Gap Control and Sensitivity) of PMEDM was selected to experimental investigation. The process performance is measured in terms of material removal rate (MRR) and surface finish (SR). The research outcome will identify the important parameters and their effect on MRR of Al/SiC MMC in the presence of suspended graphite (Gr) powder in a kerosene dielectric of EDM. It found that, the MRR is directly proportional to Ip and inversely proportional to the PC and duty cycle, and the SR improves at lower Ip and optimum range of PC, gap control and duty cycle. Assarzadeh and Ghoreishi, (2012), studied the dual response surface-desirability approach to process modeling and optimization of Al2O3 powder-mixed electrical discharge machining (PMEDM) parameters. He presents an effort to model and optimize the process parameters involved in powder-mixed electrical discharge machining (PMEDM). Aluminum oxide fine abrasive powders with particle concentration and size of 2.5–2.8 g/L and 45–50 μm, respectively, were added into the kerosene dielectric liquid of a die-sinking electrical discharge machine. The experiments were carried out in planning mode on a specially designed experimental set up developed in laboratory.

The CK45 heat-treated die steel and commercial copper was used as work piece and tool electrode materials, respectively. Discharge current (I), pulse-on time (Ton), and source voltage (V) were designated as the independent input variables to assess the process Abolfazl Golshan and Soheil Gohari, (2011), the study based on the influence of WEDM on surface roughness and volumetric material removal rate was carried out. The nonlinear polynomial models were developed for volumetric material removal rate and average surface roughness were used for optimization. In this study, a multi-objective evolutionary algorithm regarding efficient methodology, NSGA-II, was exploited for optimization of machining parameters in cold-work steel 2601. The emphasis must be put on providing a preferred solution for the process engineer in the short period of the time. The choice of one solution over other ones is dependent on the requirements of process engineer. If the requirement is based on a better surface roughness, or a maximum volumetric material removal rate, an appropriate combination of variables can be selected accordingly. Moreover, this method contributes to increase production rates noticeably via reducing machining time. KuldeepOjha, Garg and Singh, (2011), carried out quantitative analysis of EN-8 steel. Chromium powder particles are mixed in dielectric fluid. Current, powder concentration and electrode diameter are significant factors affecting both MRR and TWR. Increase in powder concentration will lead to increase in MRR. TWR increase with lower range of powder concentration but then decrease. Increase in tool diameter results in decreasing tool wear. Sukhjeet Singh, Harpreet Singh, Jasbir Singh and Rakesh Bhatia, (2011), designed a separate tank for better circulation of the powder mixed dielectric in which a stirring system is employed. Variations of EDM performance outputs, namely, material removal rate (MRR) and tool wear rate (TWR) were experimentally investigated for various machining parameters; peak current, pulse on time, pulse off time, electrode lift time, and gap spark time for different powder mixed dielectric fluid compositions. The machining tests were conducted on ASTM A681 D3 die steel work piece using copper electrodes with Al2O3 and TiC mixed EDM oil (dielectric) at different powder concentrations and pulse time settings. The results have shown that the type and concentration of the powders mixed into the dielectric and the pulse time have a significant effect on the EDM outputs. Anil Kumar, SachinMaheshwari, Chitra Sharma and Naveen Beri, (2010), studied the influence of aluminium powder (grain sizes) and concentration on machining characteristics of powder mixed EDM of nickel based super alloy (Inconel 718) with round copper electrode. The machining characteristics are evaluated in terms of material removal rate, surface roughness and wear ratio. It is found that aluminium powder mixed in dielectric medium in EDM significantly affect the machining performance. Peak material removal rate and minimum surface roughness is obtained with 6g/l fine aluminium powder grains in dielectric medium. MM Rahman, MdAshikur Rahman Khan, K.Kadirgama M, M.Noor and RosliA.Bakar, (2010), investigated that MRR is influenced by peak current and pulse on time, MRR increases with current and as well as pulse on time.

Empirical values of EDM parameters for optimum machining efficiency are 30A peak current, 400 µs pulse on time and 50 µs pulse interval in the case of MRR. Similarly 12A peak current, 10 µs pulse duration and 280 µs pulse off time settings allow the optimal tool wear rate. Paramjit Singh, Anil Kumar, Naveen Beri and Vijay Kumar, (2010), studied the effect of aluminium powder mixed in the dielectric fluid of EDM on the machining characteristics of Hastelloy. Concentrations of aluminium powder and grain size of powder are taken as process input parameters. Material removal rate, tool wear rate, percentage Wear Rate, surface roughness are taken as output parameters to measure process performance. The experimental investigations were carried out using copper electrode. Study indicates that both the input parameters strongly affect the machining performance of Hastelloy. The addition of aluminium powder in dielectric fluid increases MRR decreases TWR and improves surface finish of Hastelloy. SauravDatta *et al.,* (2010), an attempt has been made to establish mathematical models to highlight parametric influence on three selected process responses: material removal rate, surface roughness value and width of cut. Response Surface Method has been found efficient for prediction of process responses for various combinations of factor setting. Apart from modeling and simulation, application of grey based Taguchi technique has been utilized to evaluate optimal parameter combination to achieve maximum MRR, minimum roughness value and minimum width of cut; with selected experimental domain. Kuldeep Ojha, Garg, Singh (2010) In their paper, review of EDM research work related to MRR improvement has been presented along with some insight into the basic EDM process and material removal mechanism. The major research development resulting in improvement in material removal rate is summarized in Table 1in chronological order. It is found that the basis of controlling and improving MRR mostly relies on empirical methods. This is largely due to stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters along with their complicated interrelationship. Being an important performance measure, the MRR has been getting overwhelming research potential since the invention of EDM process, and requires more study/experimentation/modeling in future. Kuldeep Ojha, Garg, Singh (2010) mixed Micro nickel powder particles in EDM dielectric fluid and with the help of RSM they have concluded that the Current is most dominant factor affecting both MRR and TWR. Both the performance measures were observed an increasing trend with increase in current for any other settings of parameters MRR shows increasing trend for increase in powder concentration. The trend shows that MRR will increase further with further increase in concentration MRR increase with duty cycle but its effect is not so dominant Maximum MRR is observed for a tool diameter of 12 mm. MRR shows decreasing trend both below and above 1 2 mm tool diameter range Influences of tool diameter and duty cycle are not so dominant on TWR The confirmation tests showed that the error between experimental and predicted values of MRR and SR are within permissible range. Anil Kumar, Sachin Maheshwari, Chitra Sharma and Naveen Beri, (2010), They have identified that the significant process parameters and optimizes the machining conditions in the presence of graphite powder in the dielectric fluid to get maximum MR from Inconel 718 super alloy. The following conclusions are drawn from their work:

- Selected EDM process parameters and fine graphite powder concentration affects the machining rate in AEDM.
- Additive mixed EDM enhance machining rate appreciably.
- Peak current contribute maximum to machining rate i.e81.3%
- Contribution of fine graphite powder is 2.4%5. Overall machining rate after addition of graphite powder improves by 26.85%.

Sanjeev Kumar and Rupinder Singh (2010) have investigated that for Favorable machining conditions of surface alloying from suspended powders are found to be low peak current, shorter pulse on-time, longer pulse off-time, and negative polarity of the tool electrode. All the three input process parameters emerged as significant toward the response characteristic of micro hardness with peak current being the most significant factor with 83.41% contribution. More importantly, this study establishes the significance of pulse off-time along with peak current and pulse on-time for the phenomenon of material transfer. It can be concluded that long idle times are required for the work surface to cool down and absorb the products of sparking. Farhad Kolahan and Mohammad Bironro, (2009), proposed mathematical model using regression method to analyze the effects of machining parameters on the machining characteristics in the PMEDM process. In this regard, the effects of four machining parameters (grain size of aluminum powder, concentration of the powder, discharge current and pulse on time) on the important process outputs, including metal removal rate and electrode wear rate, have been investigated. Powder used: Aluminium, workpiece material: Tungsten Cobalt alloy, electrode material: copper and dielectric fluid: Commercial grade mineral oil. A genetic algorithm procedure has been employed to optimize the process parameters for any set of desired outputs. Kuang-Yuan Kung, Jenn-TsongHorng and Ko-Ta Chiang, (2009), studied the effect of powder mixed electrical discharge machining (PMEDM) of cobalt-bonded tungsten carbide (WC-Co) on MRR and EWR. Powder used: Aluminium, electrode material: copper, dielectric fluid: Commercial grade mineral oil (EDM-44). Processing parameters such as discharge current, pulse on time, grain size, and concentration of aluminum powder for the machinability evaluation of MRR and EWR were considered. Tomadi, Hassan, Hamedon, Daud and Khalid (2009) had carried out experiment on tungsten carbide with copper tungsten as electrode. Full factorial design of experiment method was carried out to optimize the process. In the case of the surface roughness parameter, the most influential factors were voltage followed by the pulse off time, while the peak current and pulse on time was not significant at the considered confidence level.

In order to obtain a good surface finish in the case of tungsten carbide, low values should be used for peak current, pulse off time and voltage. In the case of material removal rate, it was seen that pulse on time factor was the most influential, followed by voltage, peak current, and pulse off time. In order to obtain high values of material removal rate for the case of tungsten carbide, within the work interval considered in this study, one should use, high values for peak current and voltage. Finally, in the case of electrode wear, it was observed that the most influential were pulse off time, followed by the peak current factor. Therefore, in order to be able to obtain low values of electrode wear, high values of the pulse off time and low values peak current should be used. Shabgard and Shotorbani (2009) conducted experiment on FW4 welded steel to consider the machining characteristics in EDM process. They used the regression technique for representing the relation between machining characteristics and EDM input process parameters, to optimize the input parameters and to achieve specific output parameters, and a higher efficiency can be determined. For all values of peak current surface roughness increases with increase of pulse on time in the range of low pulse on time settings, also surface roughness increases with increase in voltage. Kansal *et al.,* (2008), developed an axi symmetric two-dimensional model for PMEDM by using the finite element method (FEM). The model utilizes the several important aspects such as temperature sensitive material properties, shape and size of heat source percentage distribution of heat among tool, workpiece and dielectric fluid, pulse on/off time, material ejection efficiency and phase change etc. to predict the thermal behavior and material removal mechanism in PMEDM process. The effect of various process parameters on temperature distributions along the radius and depth of the workpiece has been reported.

Experimental Design

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments the process of planning the experiment is carried out, so that appropriate data will be collected and analyzed by statistical methods resulting in valid and objective conclusions. When the problem involves data that are subjected to experimental error, statistical methodology is the only objective approach to analysis. Thus, there are two aspects of an experimental problem: the design of the experiments and the statistical analysis of the data. These two points are closely related since the method of analysis depends directly on the design of experiments employed. The advantages of design of experiments are as follows:

Numbers of trials is significantly reduced.

- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental error can be estimated.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

By conducting screening experimentation it is concluded that out of five process parameter such as Peak current (Ip), Pulse on time (Ton), pulse off time (Toff), Gap voltage (Vg) and Powder concentration (PC) only three most significant parameters i.e. Peak current (Ip), Pulse on time (Ton) and Powder concentration (PC) were considered for final experimentation while other parameters are kept constant. Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical techniques. It includes both upstream and shop-floor quality engineering. Upstream methods efficiently use small-scale experiments to reduce variability and remain cost-effective, and robust designs for large-scale production and market place. Shop-floor techniques provide cost-based, real time methods for monitoring and maintaining quality in production. The farther upstream a quality method is applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi's philosophy is founded on the following three very simple and fundamental concepts.

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviations from the target.
- The product or process should be so designed that it is immune to uncontrollable environmental variables.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi proposes an “off-line” strategy for quality improvement as an alternative to an attempt to inspect quality into a product on the production line. He observes that poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product. Taguchi recommends a three-stage process: system design, parameter design and tolerance design. In the present work Taguchi’s parameter design approach is used to study the effect of process parameters on the various responses of the end milling process. For conducting the experiments, it has been decided to follow the Taguchi method of experimental design and an appropriate orthogonal array is to be selected after taking into consideration the design variables. The orthogonal array was to be selected for four design variables (namely peak current, pulse on-time, pulse off-time and gap voltage) which would constitute the orthogonal array. The most important outputs are material removal rate, tool wear rate and surface roughness as the same have been selected as response parameters for this research work also. The effect of the variation in input process parameter will be studied on these three response parameters and the experimental data will be analyzed as per Taguchi method to find out the optimum machining condition.

Selection of Orthogonal Array and Parameter Assignment

In this experiment, there are four parameters at two levels each. The degree of freedom(DOF) of a two level parameter is 1 (number of levels-1), hence total DOF for the experiment is 4. The DOF of the orthogonal array selected should have higher than that of total DOF of the experiment.

Table 1. Parameters and their DOF

Input parameters	DOF
Current	1
Ton	1
Powder concentration	1

Sum of all DOF is 3.So we will take L8 orthogonal array

Table 2. Orthogonal Array Information

OA	Number of rows	Maximum no. of factor	Maximum number of Columns			
			2-Level	3-Level	4-Level	5-Level
OA2	4	3	3	-	-	-
OA8	8	7	7	-	-	-
OA9	9	4	-	4	-	-
OA12	12	11	11	-	-	-
OA16	16	15	15	-	-	-
OA16[1]	16	5	-	-	5	-
OA18	18	8	1	7	-	-
OA25	25	6	-	-	-	6
OA27	27	13	-	13	-	-
OA32	32	31	31	-	-	-
OA32[1]	32	10	1	-	9	-
OA36	36	23	11	12	-	-
OA36[1]	36	16	3	13	-	-

Signal-to-noise ratio

Noise factors are those that are either too hard or uneconomical to control even though they may cause unwanted variation in performance. It is observed that on target performance usually satisfies the user best, and the target lies under acceptable range of product quality are often inadequate. If Y is the performance characteristic measured on a continuous scale when ideal or target performance is T then according to Taguchi the loss caused L(Y) can be modeled by a quadratic function as shown in equation (1)

$$L(Y) = K(Y \quad T2) \ldots\ldots\ldots (1)$$

The objective of robust design is specific; robust design seeks optimum settings of parameters toachieve a particular target performance value under the most noise condition. Suppose that in a set of statistical experiment one finds a average quality characteristic to be μ and standard deviation to be σ. Let desired performance be $\mu 1$ .Then one make adjustment in design to get performance on target by adjusting value of control factor by multiplying it by the factor(μ_0/μ).Since on target is goal the loss after adjustment is due to variability remaining from the new standard deviation. Loss after adjustment shown in equation (2):

$$k(\mu_0/\mu)^2\sigma^2 \ldots\ldots\ldots (2)$$

The factor (μ^2/σ^2) reflects the ratio of average performance μ^2(which is the signal) and σ^2 (the variance of performance) the noise. Maximizing (μ^2/σ^2) or S/N ratio therefore become equivalent tominimizing the loss after adjustment. Finding a correct objective function to maximize in an engineering design problem is very important. Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Higher the Better If the nominal value for a characteristic Y is best then designer should maximize the S/N ratio
i.e:
$(S/N)_{HB} = -10 \log (MSD)_{HB}$
Where,
$MSD_{HB} = 1/R \sum_{j=1}^{R}(\frac{1}{y_j^2})$
Smaller the Better:
$(S/N)_{LB} = -10 \log (MSD)_{LB}$
Where,
$MSD_{LB} = 1/R \sum_{j=1}^{R}(y_j^2)$

In our research MRR is considered larger is better. Value of MRR is measured by difference between initial and final weight after machining TWR and SR is considered as smaller is better. Value of TWR is measured by difference between initial and final weight after machining and value of SR is measured with the help of surface roughness tester.

Experimental Details

The main objective was to increase MRR, reduce TWR and SR during the machining process. The experiment were done with AISI D3 steel, copper tool and DEF-92 EDM oil. The work piece material taken for this study was AISI D3 steel. It is an air hardening, high-carbon, high-chromium tool steel. It displays excellent abrasion/wear resistance and has good dimensional stability and high compressive strength. It is heat treatable and will offer hardness in the range 58-64 HRC.
Typical applications for D3 Steel:

- Blanking and forming dies
- Forming rolls
- Press tools
- Punches
- Bushes

All experiments were conducted on Electronica EDM machine in a workshop, Kandivali, Mumbai. The diameter of the cylindrical copper tool was 20mm. Two levels were selected for each input parameter.

Table 3. Parameters and their levels

Factor	Units	Coded Value	-1	+1
Peak current	Amp.	IP	10	20
Pulse on time	µsec.	T_{ON}	40	80
Powder conc.	gm/liter	PC	0	10

Experimental Result

The Taguchi design experiments were conducted to study the effect of process parameters over the output response characteristics with the process parameters and interactions assigned to columns as given in Table and 8 experiments were conducted using Taguchi experimental design methodology. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software.

Analysis of experiment with Silicon (Si) Powder

Table 4. Analysis of experiment with silicon (Si) Powder

Sr.No	Ip	PC	Ton	MRR	TWR	SR
1	10	10	80	20.0310	0.1901	8.824
2	10	0	80	13.135	0.1823	9.145
3	10	10	40	19.6581	0.1881	8.892
4	10	0	40	14.6581	0.1881	8.892
5	20	10	80	45.1282	0.9912	18.462
6	20	10	40	42.3076	0.9560	17.214
7	20	0	40	26.141	0.8512	16.895
8	20	0	80	25.131	0.8141	17.914

I. General Linear Model

General Linear Model: MRR versus Ip, PC, Ton

Method
Factor coding (-1, 0, +1)
Factor Information

Factor Type Levels Values
Ip Fixed 2 10, 20
PC Fixed 2 0, 10
Ton Fixed 2 40, 80

Table 5. Analysis of Variance for Means (MRR)

Source	DF	Adj SS	Adj MS	F	P
Ip	1	634.14	634.136	32.00	0.005
PC	1	288.72	288.718	14.57	0.019
Ton	1	0.05	0.055	0.00	0.961
Error	4	79.28	19.820		
Total	7	1002.19			

DF - degrees of freedom, SS - sum of squares, MS – mean squares (Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ - determines significance of a factor at 95% confidence level.

Regression Equation

MRR = 25.77 - 8.90 Ip_10 + 8.90 Ip_20 - 6.01 PC_0 + 6.01 PC_10 - 0.08 Ton_40 + 0.08 Ton_80

General Linear Model: TWR versus Ip, PC, Ton

Method
Factor coding (-1, 0, +1)
Factor Information
Regression Equation
MRR = 25.77 - 8.90 Ip_10 + 8.90 Ip_20 - 6.01 PC_0 + 6.01 PC_10 - 0.08 Ton_40 + 0.08 Ton_80

General Linear Model: TWR versus Ip, PC, Ton

Method
Factor coding (-1, 0, +1)
Factor Information

Factor Type Levels Values
IpFixed 2 10, 20
PC Fixed 2 0, 10
Ton Fixed 2 40, 80

Table 6. Analysis of Variance for Means(TWR)

Source	DF	Adj SS	Adj MS	F	P
Ip	1	1.02524	1.02524	382.77	0.000
PC	1	0.01049	0.01049	3.92	0.119
Ton	1	0.00000	0.00000	0.00	0.971
Error	4	0.01071	0.00268		
Total	7	1.04645			

Regression Equation

TWR = 0.5451 - 0.3580 Ip_10 + 0.3580 Ip_20 - 0.0362 PC_0 + 0.0362 PC_10 + 0.0007 Ton_40 - 0.0007 Ton_80

General Linear Model: SR versus Ip, PC, Ton

Method
Factor coding (-1, 0, +1)
Factor Information

Factor Type Levels Values
IpFixed 2 10, 20
PC Fixed 2 0, 10
Ton Fixed 2 40, 80

Table 7. Analysis of Variance for Means(SR)

Source	DF	Adj SS	Adj MS	F	P
Ip	1	150.789	150.789	796.64	0.000
PC	1	0.037	0.037	0.20	0.680
Ton	1	0.752	0.752	3.97	0.117
Error	4	0.757	0.189		
Total	7	152.335			

Regression Equation

SR = 13.280 - 4.341 Ip_10 + 4.341 Ip_20 - 0.068 PC_0 + 0.068 PC_10 - 0.307 Ton_40 + 0.307 Ton_80

II. Main Effect Plot and S/N Ratio Plot

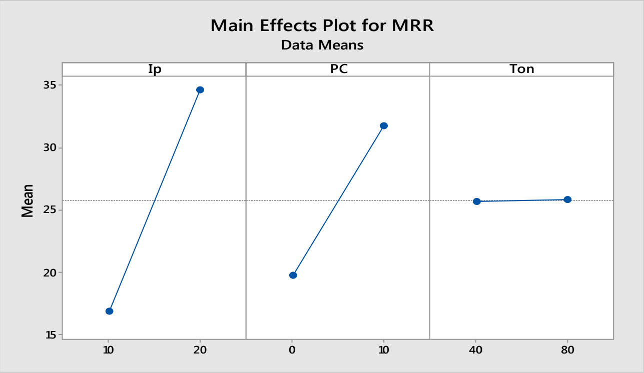

Fig. (a). Main effects plot for MRR

Main effect plot for MRR(material removal rate) of D3 die steel is shown in fig.(a) MRR(material removal rate) has linear variation with increase in Ip (Input current), As Ip(Input current),PC and Ton(pulse on time) increases, MRR also increases.

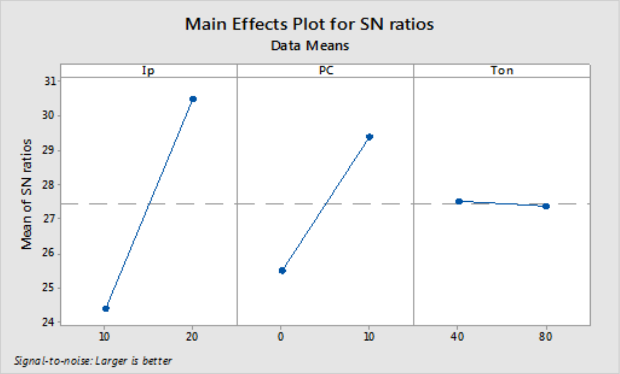

Fig. (b). Main effects plot for SN ratios

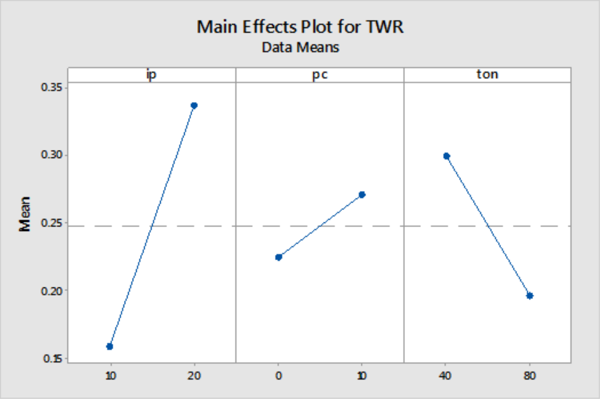

Fig. (c). Main effects plot for TWR

Main effect plot for TWR(tool wear rate) of copper electrode is shown in fig (c) .TWR has liner relation with Ip TWR increases with the increase in Ip but there is a slight decrease in it when powder concentration is increased.

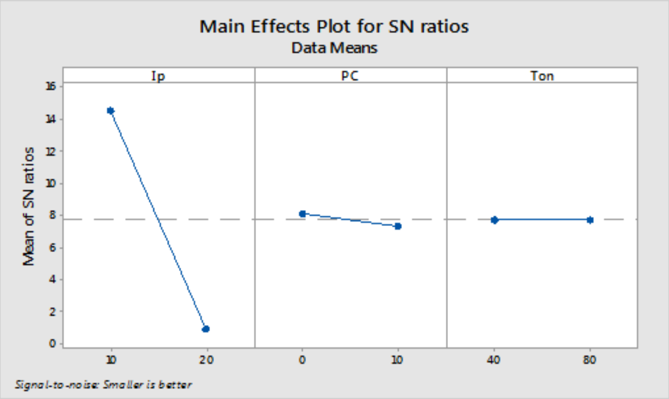

Fig. (d). Main effects plot for SN ratios

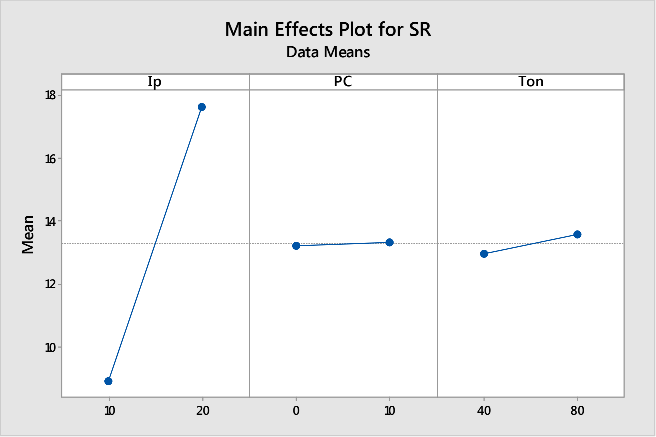

Fig. (e). Main effects plot for SR

Main effect plot for Ra(Surface Roughness) of D3 die steel is shown in fig.(e).Ra (Surface Roughness) has linear variation with Ip and almost constant for PC. SR slightly increases with the increase in Ton.

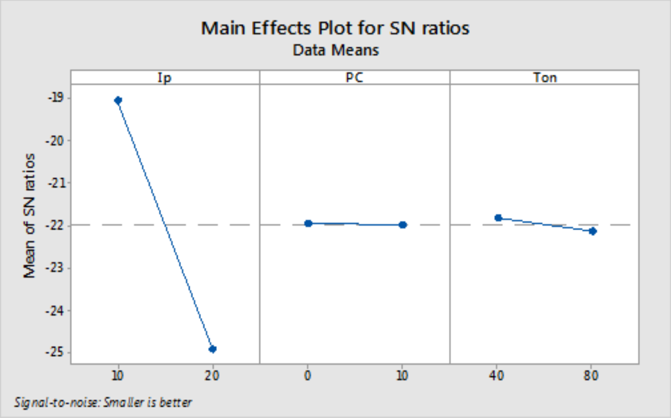

Fig. (f). Main effects plot for SN ratios

Interaction Plot

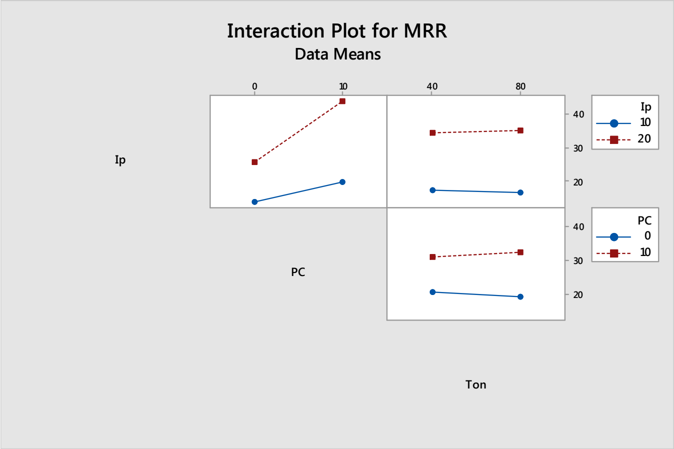

Fig. (g). Interaction plot for MRR

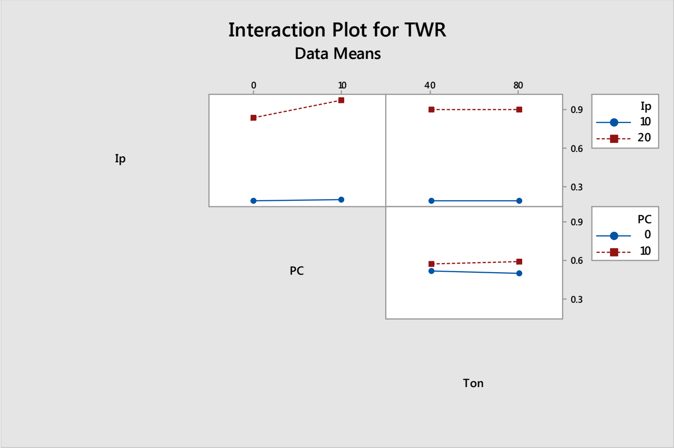

Fig. (h). Interaction plot for TWR

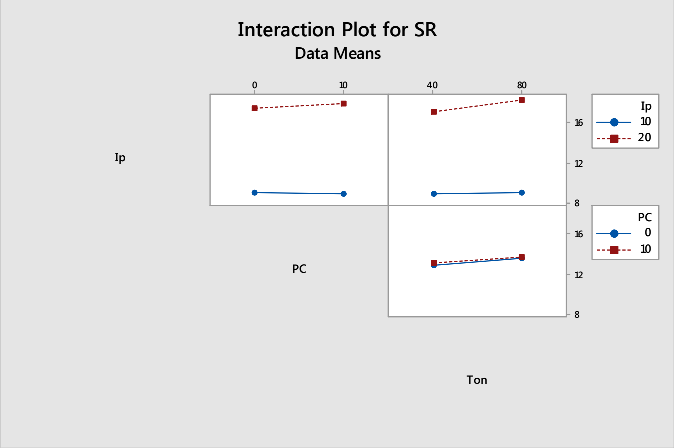

Fig. (i). Interaction plot for SR

Confirmation Experiments

The final step of the Taguchi method is the confirmationexperiments conducted for examining the qualitycharacteristics. The model used in the confirmation tests isdefined with the total effect generated by the controlfactors. Three confirmation experiments are performed tovalidate the above analysis conclusions.

Confirmation experiments

Response table for MRR

From mean of each level of every factor we will construct response table for MRR which are given below

Table 8. Response table for MRR

Level	Ip	PC	Ton
1	24.40	25.51	27.52
2	32.02	29.38	27.37
Delta	6.09	3.87	0.14
Rank	1	2	3

$\eta_m = 27.7$

From above main effect plot of MRR we can conclude the optimum condition for MRR is:

(IP_2–PC_2 –Ton_2)

$$\eta_{opt} = \eta_m + \sum_{i=1}^{0} (\bar{\eta}_i \quad \eta_m)$$

$$= 27.7 + (32.02 \quad 27.7) + (29.38 \quad 27.7) + (27.37 \quad 27.7)$$

$$= 33.37$$

$$y_{opt}^2 = \frac{1}{10^{\frac{-\eta_{opt}}{10}}}$$

$y_{opt} =$ 46.61(Theorotical)

$y_{opt} =$ 45.1282(Experimental)

Response table for TWR

From mean of each level of every factor we will construct response table for TWR which are given below

Table 9. Response table for TWR

Level	Ip	PC	Ton
1	14.5573	8.1206	7.7037
2	0.9134	7.3500	7.7670
Delta	13.6439	0.7705	0.0633
Rank	1	2	3

$\eta_m = 7.7353$

From above main effect plot of MRR we can conclude the optimum condition for TWR is:
(IP_1–PC_1 –Ton_2)

$$\eta_{opt} = \eta_m + \sum_{i=1}^{0} (\bar{\eta}_i \quad \eta_m)$$

$$= 7.7353 + (14.5573 \quad 7.7353) + (8.1206 \quad 7.7353) + (7.7670 \quad 7.7353)$$

$$= 14.2037$$

$$y_{opt}^2 = 10^{\frac{-\eta_{opt}}{10}}$$

$y_{opt} =$ 0.1949(Theorotical)

$y_{opt} =$ 0.1881(Experimental)

Response table for SR

From mean of each level of every factor we will construct response table for SR which are given below

Table 10. Response table for SR

Level	Ip	PC	Ton
1	-19.02	-21.96	-21.81
2	-24.92	-21.98	-22.13
Delta	5.89	0.03	0.32
Rank	1	2	3

$\eta_m =$ 21.97

From above main effect plot of MRR we can conclude the optimum condition for MRR is:

(IP_1–PC_1 –Ton_1)

$$\eta_{opt} = \eta_m + \sum_{i=1}^{0}(\bar{\eta}_i \quad \eta_m)$$

$$\begin{aligned} &= 21.97 + (\ \ 19.02 + 21.97) \\ &\quad + (\ \ 21.96 + 21.97) \\ &\quad + (\ \ 21.81 + 21.97) \\ &= 18.85 \end{aligned}$$

$$y_{opt}^2 = 10^{\frac{-\eta_{opt}}{10}}$$

$y_{opt} =$ 8.754(Theorotical)

$y_{opt} =$ 8.892(Experimental)

Final confirmation is done by comparing the theoretical and experimental result of output parameters and calculating the error. If the calculated error is under the specified value then experiment is successful.

Table 11. Result analysis

Response Variables	Input parameters			Predicted Value	Experimental Value	Error
	Ip	PC	Ton			
MRR	20	10	80	46.61	45.1282	3.18%
TWR	10	0	80	0.1949	0.1881	3.48%
SR	10	0	40	8.754	8.892	1.57%

From analysis of table VIII, it can be observed that the calculated error is small. The error between experimental and predicted values of MRR and SR lies within ±10%. This confirms excellent reproducibility of the experimental conclusion.

Conclusion

The objective of this work is to study the effect of powder mixed dielectric (PMEDM) upon important parameters of EDM i.e. material removal rate, tool wear rate and surface roughness. The machine has the capability to vary the peak current, pulse on time, pulse off time , gap voltage etc. Considering the capability of the machine and the output required for the experimentation, peak current, pulse on time and powder concentration were decided to taken as the input variables and all other factors have kept constant. Powder mixed into DEF-92 EDM oil in order to study the effect of PMEDM on machining performance of AISI D3 steel. To obtained the desired levels for final experimentation with minimum possible number of experiment. By conducting experiments it is concluded that Current has major influence on material removal rate, tool wear rate and on surface roughness. As current increases, the stronger spark is generated so melting starts at earlier which ultimately results in higher MRR, also spark energy is low at lower discharge current. Addition of powder in dielectric enhances the material removal rate with lower surface roughness. Also pulse on time has considerable influences on MRR. Aluminium powder, Silicon powder, have shown significant effect on machining of AISI D3 Die Steel with Dielectric DEF-92 EDM oil. Enhanced material removal rate and lower TWR and SR have been achieved. Analysis was done by ANOVA which led to the following conclusion about the variation of response parameters in terms of independent parameters within the specified range. The result obtained from the present study is extremely helpful for selecting the optimum machining conditions for AISI D3 die-steel work material, which is extensively used in moulds and dies making industries.

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