Investigation of powder mixed electrical discharge machining and process parameters optimization using Taguchi based overall evaluation criteria

M.Ashok¹, T.Niranjan², S.Chokalingam³and B.Singaravel¹

¹Department of Mechanical Engineering, Vignan Institute of Technology and Science, Hyderabad, Telangana-508284.
²Department of Mechanical Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana-500075,-Telangana, India.
³Department of Mechanical Engineering, E.G.S.Pillay Engineering College, Nagapattinam,TamilNadu, India.

Email: singnitt@gmail.com

Abstract: Electrical Discharge Machining is a type of nontraditional process can be used for machining of hard materials and making of complicated shape. In EDM, the important parameters are tool, workpiece and dielectric liquid. Dielectric liquid is used to enhance ionization during the process. Powder Mixed EDM (PMEDM) is preferred for enhance the process efficiency. In this work, nano alumina (Al₂O₃) powder is added to the dielectric liquid and the process parameters effects are investigated. Input parameters considered are pulse on time, pulse off time and current. Output parameters considered are rate of material removal, surface quality and wear in electrode. Nano powders are mixed in the ratio of 2% to the EDM oil during the operation with dielectric fluid weight ratio. Process parameters are optimized using Taguchi based Overall Evaluation Criteria (OEC). The result revealed that PMEDM is enhanced the process efficiency.

1. Introduction

EDM is widely preferred nontraditional process which is considered to process hard materials and making intricate shapes. EDM process plays a significant function in manufacturing sector and marketing around the world [1, 2]. The process efficiency enhancement in EDM process is an important task. In this work, two methods are used to improve the efficiency of machining process. Powders are mixed in dielectric liquid [3] and process parameters optimizations [4] are the important methods.

Powder mixed EDM is approached for elimination of conventional drawbacks such as high electrode wear and poor surface quality. In this regard, micro or nano powders are added with appropriate proportion to the dielectric liquid. The important functions of PMEDM are lowering the dielectric breakdown properties, wide the spark gap, flushing uniformity and stable in spark [5-8]. Optimization of process parameters are used to enhance the efficiency in machining. Taguchi is a standard optimization tool for solving problems in science and engineering problems [9]. But, it has a limitation for dealing
single output and its analysis. But in real case engineering industries problems are multiple outputs [10]. Hence, there is a need for Taguchi method is hybrid with other approaches for solving multiple objective problems. Generally, Taguchi method is used to combine with grey relational analysis, utility concept and desirability analysis. But in this work, an approach of overall evaluation criterion is combined with Taguchi method for solving multiple objective optimization problems.

2. Literature review

Mohanty et al. [5] conducted an investigation of nano powder added dielectric liquid and its performance in spark erosion process. The process parameters effects on responses were investigated during machining of Al-MMC. Response surface methodology and metaheuristic approaches were used. The outcomes of the investigation was revealed that nano powder added dielectric liquid based spark erosion process was enhanced the machining performance. Kumar et al. [6] investigated the performance of nano powder mixed EDM on dielectric fluid during machining of Inconel 825. They have pointed about problems during EDM process are low MRR and higher SR. To overcome these issues nano Al2O3 added in dielectric fluid and the result concluded that improvement in surface related issues. Mohanty and Routara [7] conducted a review process of nano particle added in dielectric fluid and their performances. Nano powders in dielectric liquid lowers the dielectric strength and improves spark development between the electrodes. Hence, it is noticed that improved MRR and reduced SR with process stability. Harmesh Kumar [8] used nano powder added dielectric fluid in EDM process to enhance surface finish. Carbon nano tube mixed with different proportion and their surface characteristics during machining of AISI D2 steel. The improvement in SR and MRR is obtained using proposed powder mixed into the dielectric fluid.

Krishna and potwari [11] investigated that electric discharge coating process and parameters were optimized using Taguchi based OEC process. The proposed optimization method of Taguchi based OEC is capable of solving multiple objective problems effectively. Oztop et al. [12] used Taguchi based OEC method for process parameter optimization of microwave parameters during potato slices frying process. The optimized process parameters of microwave process were enhanced the potato slices frying process. Shukla et al. [13] investigated formability of titanium alloy using Taguchi based OEC method. This process was capable of solving simultaneous and multiple objective problems efficiently. Wangikar et al. [14] conducted process parameters optimization study using Taguchi based OEC method. The result revealed that optimized process parameters significantly influence the responses.

From the literature review, limited studies are available with nano powder mixed dielectric liquid and its process parameters optimization. Taguchi method is generally combined with grey concept, utility concept and desirability approach. In this work, an attempt is made using Taguchi based overall evolution criteria is attempted for process parameters optimization of EDM process.

3. Experimental Setup

Die sinking EDM setup is used to conduct spark erosion process on P20 steel as workpiece. P20 steel is widely preferred for low temperature application like dies in die casting process and molds in injection molding process. Copper is used as electrode material (12 mm diameter) which is commercially readily available and easy to machine. The important process parameters selected are pulse on time, pulse off time and current. Experiments are designed based on Taguchi orthogonal array. Three parameters and three levels are considered. Hence, Taguchi L9 orthogonal array is used to execute the machining process [15, 16]. These parameters are chosen based on preliminary experiments and past literatures. Table 1 shows the values of process parameters used. Process performance parameters are considered such as Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR). The nano particles added are Al2O3 in composition of 2% to the EDM oil. Fig 2 shows the machined sample. An electrically operated stirrer is used for avoiding agglomeration of nano Al2O3 during the process.
The responses of spark erosion process are measured the following equations (1) and (2).

\[ MRR = \frac{W_{wbm} - W_{wan}}{t \times \rho} \frac{mm^3}{min} \] (1)

\[ TWR = \frac{W_{ebm} - W_{eam}}{t \times \rho} \frac{mm^3}{min} \] (2)

Where, \( W_{wbm} \) represents the workpiece weight before erosion (gm); \( W_{wan} \) represents the workpiece weight after erosion (gm); \( t \) indicates time taken for machining (min) and \( \rho \) indicates the density of workpiece and electrode material (gm/cm³). Machined surface profile (i.e. average surface roughness) is measured using Mitutoyo SJ-210 surface roughness tester [17]. Experimental observations are displayed in Table 2.

| Sl.No | Parameters     | Level 1 | Level 2 | Level 3 |
|-------|----------------|---------|---------|---------|
| 1     | Pulse on time  | 500     | 600     | 700     |
| 2     | Pulse off time | 300     | 400     | 500     |
| 3     | Current        | 5       | 6       | 7       |

Table 1. Process parameters and their values

Figure 1. EDM Machine

Figure 2. Machined samples
Table 2. Experimental results

| Sl.No | Pulse on time (µs) | Pulse off time (µs) | Current (Amps) | MRR (mm³/min) | TWR (mm³/min) | SR (µm) |
|-------|-------------------|-------------------|---------------|--------------|--------------|--------|
| 1     | 500               | 300               | 5             | 1.582        | 0.081        | 2.52   |
| 2     | 500               | 400               | 6             | 2.148        | 0.187        | 2.85   |
| 3     | 500               | 500               | 7             | 2.567        | 0.193        | 3.12   |
| 4     | 600               | 300               | 6             | 3.472        | 0.217        | 3.87   |
| 5     | 600               | 400               | 7             | 4.834        | 0.281        | 4.16   |
| 6     | 600               | 500               | 5             | 4.121        | 0.251        | 3.94   |
| 7     | 700               | 300               | 7             | 5.327        | 0.312        | 4.63   |
| 8     | 700               | 400               | 5             | 4.821        | 0.285        | 5.17   |
| 9     | 700               | 500               | 6             | 5.142        | 0.298        | 4.51   |

4. Methodology

Optimization of process parameters can be used to enhance the production capability and functional characteristics of machined components. This can be categorized into single objective and multi objective optimization problems [18]. In single objective optimization method, one response can be analyzed at a time. The best example of single objective optimization problem is standard Taguchi method. In case of multi objective optimization problems, there is a need of set of procedure for solving multiple objectives simultaneously. Taguchi based grey relational analysis is the best example for multi objective optimization technique. When a process is under study to satisfy more than one response, the samples tested for each trial conditions are evaluated by multi criteria evaluation, which can be combined into single quantity called OEC for the given sample. In this evaluation each response may have different units of measure, quality characteristics and relative weighting [11-14]. The following procedures are adopted for Taguchi based OEC method.

1. Selection of quality characteristics
   MRR, TWR and SR are the quality characteristics considered. MRR is the maximization type objective. TWR and SR are the minimization objectives.

2. Design of experiments
   Three parameters and three levels are considered. Based on this, Taguchi L₉ orthogonal array is used to execute the experiments.

3. Analysis of results and selection of optimum process parameters
   The considered quality characteristics are used to enhance the process. The demand appropriate consideration to significant combination of evaluation using different criteria, then these quality characteristics is converted into single equivalent index using OEC technique. The following equation are used to bring singe equivalent criteria function by normalizing the output data and assigning the relative importance

   \[
   OEC = \left(1 - \frac{(S_1 - W_1)}{(B_1 - W_1)}\right) \times RW_1 + \left(1 - \frac{(S_2 - W_2)}{(B_2 - W_2)}\right) \times RW_2 + \left(1 - \frac{(S_3 - W_3)}{(B_3 - W_3)}\right) \times RW_3
   \]

   Where W indicates the minimum value, B indicates the maximum value, RW indicates the relative weights, and S indicates the sample value, 1 = SR, 2 = TWR, and 3 = MRR

4. ANOVA method
To observe the significant effect of process parameters and to evaluate the experimental results ANOVA method is used. OEC is used to make compatible units of measure with its distinct quality characteristics for proper relative weight criterion. The weight of each parameter is assumed as equal. In this analysis, MRR, TWR and SR are selected as responses. Table 3 shows the description of evaluation criteria.

| Criterion | Maximum Value | Minimum Value | Relative Weight (%) | Objective function |
|-----------|---------------|---------------|---------------------|--------------------|
| SR        | 14.52         | 3.98          | 33.3                | Minimization       |
| TWR       | 21.83         | 10.11         | 33.3                | Minimization       |
| MRR       | -8.028        | -14.26        | 33.3                | Maximization       |

The overall evaluation criteria are calculated by equation (3) based on the specified objective function considering their relative weights and the values are shown in Table 4.

| Sl.No | OEC values |
|-------|------------|
| 1     | 0          |
| 2     | 6.83       |
| 3     | 16.27      |
| 4     | 42.04      |
| 5     | 83.28      |
| 6     | 61.56      |
| 7     | 98.96      |
| 8     | 84.81      |
| 9     | 93.17      |

Figure 3. Main effect plot for OEC
ANOVA approach is used to find the significant effect of input parameters (independent variable) on responses (dependent variable). These effects can be determined in terms of percentage contribution. It contains degree of freedom, sum of squares and percentage contribution. Higher percentage contribution indicates more significant effect and controls the response parameters. Also, it has an error variance in the process [19]. The results of ANOVA for the OEC value as shown in Table 5. On examining the percentage contribution of the different factors, it can be seen that the pulse on time has the highest contribution of about 91% followed by current at 5%. The main effects plot (Figure 3) shows that the optimum condition with pulse on time of 700µs, pulse of time of 400 µs and current of 7 Amps.

| Source         | Sum of Squares | Degrees of freedom | Mean Square | F-value | Prob>F | Percentage Contribution |
|----------------|----------------|--------------------|-------------|---------|--------|-------------------------|
| Pulse on time  | 2              | 11041.04           | 5520.52     | 55.80   | 0.331  | 91.04                   |
| Pulse off time | 2              | 229.54             | 114.77      | 1.160   | 0.760  | 1.892                   |
| Current        | 2              | 658.46             | 329.23      | 3.32    | 0.413  | 5.429                   |
| Error          | 2              | 197.86             | 98.93       | 1.631   |        | 1.631                   |
| Total          | 9-1=8          | 12126.92           |             |         |        | 100                     |

5. Results and discussions

The machining performance of nano powder mixed dielectric liquid and its process parameters optimization are attempted during EDM process. Surface roughness is an important machinability characteristic which influences the factional characteristics. Electrode wear influence the dimensional reproducibility and accuracy. Rate of material removal influence the production cost. Copper is used as electrode material. Taguchi based OEC method is used to optimize the process parameters. Table 2 shows the experimental results. Main effects plot is plotted using process parameters with responses during EDM process. From the main effect plots, minimum surface roughness, electrode wear and higher material removal are predicted. The optimum process parameters are 700 µs of pulse on time, 400 µs of pulse off time and 7 Amps of current. ANOVA is used to find the significance effect of each process parameters on response can be predicted. From the ANOVA results, it is understood that pulse on time and current are influenced the process efficiency.

The result indicated that the addition of powdernedelectric strength by add into dielectric fluid could be increase MRR. This is because of highly concentrated discharge and increase of spark frequency by powder mixed in dielectric liquid. This powder added dielectric fluid produces wider discharge space by increases of spark gap. This wider discharge rearranges the impact force and leads to wider and shallow depth of craters. Hence, powder added dielectric fluid provides higher MRR due to wider craters and low surface roughness due to shallow craters [5, 6]. Generally, TWR increases by spark energy and followed by heat transferred to the electrode. In this study, reduce TWR is observed with increased MRR. This is might be due to powder particles presented in inter electrode gap are used to absorb heat that are deposited to the machined surface. It is used to reduce the heat transfer to the electrode surface [7, 8]. The commonly used electrode materials are copper and brass. Electrode materials have important ant properties such as electrical (electrical conductivity) and thermal properties (thermal conductivity and melting point) which
influence the machining performance. These electrical and thermal effects lead to electrode wear. Carper has higher electrical conductivity, which is used to provide more spark distribution and followed by melting and vaporization during the process. It has better melting point than brass material. Hence, better machining process efficiency is achieved using copper as electrode material. The proposed Taguchi based OEC is used to solve multiple objective problem effectively. The significant advantage of this method is not involving any kind of constant values and assumptions.

6. Conclusion

The following conclusions are observed from the experimental result during powder mixed EDM process of P20 steel.

1. The proposed nano Al2O3 mixed dielectric fluid is given increased MRR and reduced TWR and SR.
2. Nano Al2O3 mixed dielectric fluid is used to increase spark gap and dielectric strength. It leads wider and shallow craters. Nano Al2O3 powders are low cost and it is easily available.
3. TWR is reduced due to less heat transfer in the electrode surface because of powders presented in the inner electrode gap absorbing heat during the process and transferred to the machined surface. Also, MRR is increased due to wider crater and SR is reduced due to shallow crater during the process.
4. Taguchi based OEC method is proposed for solving multiple objective problems in EDM process. The optimum process parameters are selected based on Taguchi OEC are 700 µs of pulse on time, 400 µs of pulse off time and 7 Amps of current. ANOVA concept is applied for the determination of significance effect of process parameters on response. It has simple procedure for solving multiple objective problems.

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