International Journal of Mechanical Engineering

Experimental Investigation on Electric Discharge Machining of High Carbon-High Chromium Tool Steel

J. Pradeep Kumar
Department. of Production Engineering, PSG College of Technology, Coimbatore, India.
jpk.prod@psgtech.ac.in

Jude Joel Edwin
Department. of Production Engineering, PSG College of Technology, Coimbatore, India.

Abstract

Electrical Discharge Machining (EDM) is one of the most commonly used processes to machine hardened materials which are difficult to process or machine using conventional methods. This research work has been done to determine the optimized parameters during Electrical Discharge Machining (EDM) of AISI D3 die steel. The experiments have been designed using Response Surface Methodology (RSM) Box Behnken design and the optimization is carried out using the VIKOR method which is a Multi-Criteria Decision Making (MCDM) technique. The Input parameters considered in this study are, Peak Current (Ip), Pulse on time (Ton), Gap Voltage (Vgap), and Pulse off time (Toff). The response variables considered in this study are Material Removal Rate (MRR), Surface Roughness (SR), Overcut (OC), and Parallelism. An electrolytic copper flat was used as the electrode and the AISI D3 steel was prepared in the form of round blanks. Further, the impact of the input parameters on the response variables is also analyzed, and also the percentage of contribution of input parameters on each of the response variables is also determined. The optimized combination of the input parameters obtained are Peak current (Ip) = 20A, Pulse on time (Ton) = 30µs, Pulse off time (Toff) = 9µs, and Gap voltage (Vgap) = 50V. A Scanning Electron Microscope (SEM) analysis has also been done on samples that were machined at high, medium, low and the optimized input parameter values to study the effect of machining parameters on the machined surface.

Keywords—EDM, RSM, VIKOR, AISI D3 steel, SEM analysis, Tool steel.

I. INTRODUCTION

Electrical Discharge Machining (EDM) is one of the non-traditional machining processes which is used when the workpiece material is electrically conductive and is of high hardness which makes it difficult to machine using conventional processes. In this process, material removal is achieved by electrical sparks produced in a dielectric medium because of which the base material vaporizes, and thus the material is removed. This process is also adopted when the shape required to the machine is complex and cannot be done or would be very difficult to be done by traditional processes. The general setup for an EDM process consists of a workpiece material placed in a dielectric medium and the desired final shape required in the workpiece material is formed on the tool material. As Electrical Discharge Machining (EDM) is used mostly in machining components which are critical a large amount of research is done to determine the optimum parameters and the effect of these parameters on the properties of the final product.

Alla M.Ubaid et.al. Studied the effect of input parameters on the responses like material removal rate and electrode wear rate during the machining of AISI M2 steel with copper and brass electrodes. The optimum combination for maximizing MRR and minimizing EWR was determined. This study also proved that in recent times EDM has been under extensive research which makes it a good reason to conduct this study [1]. Ali Kaylon conducted a study on the machining of caldie tool steel using graphite and copper electrodes. The optimum parameters for maximum MRR and minimum EWR, surface roughness were determined for each electrode material. Using ANOVA it was further determined that among all the input parameters discharge current was the most influencing parameter. It was further found that graphite electrodes produced a better surface finish than copper electrodes [2]. Vikas K.Shukla et.al. Performed EDM on Nimonic-80A alloy and determined the influence of input parameters discharge current and pulse on time on MRR and surface roughness. It was found that an increase in current and pulse on-time increased the MRR whereas it was the exact opposite for the pulse-off time. Finally, the optimum parameters to attain high MRR and low surface roughness were determined [3]. Sudhir Kumar et.al. Performed multi-variable optimization of EDM on AISI420 stainless steel using a combination of Taguchi and GRA. It was observed that current had the highest influence on MRR and EWR followed by voltage and pulse on time. A comparative study between Taguchi and RSM methodology was also carried out and it was determined that RSM had a better ability to accurately predict the results [4].

B. Singaravel et.al. conducted a comparative study of EDM on AISI D2 steel by using conventional EDM dielectric like kerosene against vegetable oils like Cottonseed oil and Jatropha oil. Optimization was done using a hybrid approach comprising of Taguchi and VIKOR methods. It was observed that optimization was achieved with far less computation compared to other multi-objective optimization methods [5]. Phan Nguyen Huu et.al. Utilised the MOORA technique for multiple variable optimizations of vibration-assisted EDM on SKD61 tool steel. The weights for the response variables were determined using Analytical Hierarchy Process (AHP). This study concluded that low frequency assisted vibration helped in improving machining using EDM. Further optimized parameters for high MRR and low TWR and surface roughness were determined [6]. T.R. Paul et.al. did a comparative study of MOORA and MOORA-PCA methods for optimization of EDM on Inconel 800. They considered pulse on time, pulse off, and peak current as input parameters and the response variables were MRR and surface roughness. It was found that the proposed hybrid method was as effective as the original method [7]. Nishant K. Singh et.al. predicted the MRR and surface roughness using mathematical models based on ANN, ANFIS, and RSM. The material considered in this study was AISI D3 steel, later a comparative study was done between the predicted values and the values obtained by experimentation; it was found that the predictions were almost the same and the ANFIS method, in particular, had more accurate predictions [8]. Tiago Czelusniak et.al. reviewed the types of electrode materials used in EDM over time. This study also included additively manufactured EDM electrodes, their advantages, and disadvantages [9]. Luboslav Straka and Slavomira Hasova studied the impact of input parameters on the Material Removal Rate (MRR) and Electrode Wear Rate (EWR) during the machining of EN X210Cr12 with the copper electrode. The main aim was to attain maximum MRR and minimum EWR. It was observed that as current and pulse on-time increased MRR increased, also with a constant current and increase pulse on time there was a reduction in EWR [10]. Mohammad Jafar Hada et.al. in EDM as the shape of the tool is produced on the workpiece material, a study was conducted on the effect of surface roughness of the tool on the machining performance and the final surface roughness of the machined workpiece. AISI 1050 was selected as the workpiece and copper was used as the electrode material. It was found that MRR is less when the tool surface roughness is high and TWR increases with an increase in tool surface roughness. However, the initial surface roughness of the tool has a very minimal effect on the final surface roughness of the machined surface [11]. Uttam Kumar Mohanty et.al. used the VIKOR index MCDM technique to determine the optimized parameters for machining of high carbon high chromium tool steel. ANOVA also was done to determine the influence of input parameters on the response variables. It was found that current had the highest impact on the response variables whereas voltage was the least influencing factor [12].

Vinothkumar and Pradeepkumar did a comparative study on EDM of AISI D2 steel using the conventional EDM process and the cryogenically cooled EDM process. It was found that EWR was less in the cryogenically cooled EDM process and the surface roughness of the final workpiece also is improved [13]. Muhammet gul et.al. conducted a detailed literature review of the VIKOR method and its fuzzy adaptations in different fields. It was concluded that VIKOT has its major application in Agriculture, material selection, and mechanical related disciplines [14]. Manivanan and Pradeep Kumar made use of Technique for Ordered Preference by Similarity to Ideal Solution (TOPSIS) to find out the optimized values for machining of AISI 304 Stainless steel. It was found that feed rate had the highest influence on the quality of the hole machined followed by peak current [15]. Shailesh Dewangan et.al. made use of grey-fuzzy logic to determine the optimized parameters for machining of AISI P20 tool steel. ANOVA results showed that pulse on time had the highest influence on surface roughness followed by peak current. It further showed that the grey-fuzzy technique reduced the complexity of the traditional GRA method for multi-criteria decision-making [16].

S. Dewangan et.al. carried out EDM on AISI P20 tool steel to determine the optimal parameters and based on MCDM technique of TOPSIS determine the robustness of the decision makers' preference. RSM was used to design the experiments, from the study it was determined that peak current and pulse on-time influenced the white layer thickness, and as the peak current increased the surface crack density also increased. It was also found that higher peak current and on time had a negative effect on the amount of overcut [17]. T. Muthuramalingam and B. Mohan conducted an extensive review on the effect of modeling and influence of input process parameters on the response process parameters like material removal rate, Surface roughness, and electrode wear rate in the EDM process. It was found that peak current and pulse on time had the highest impact on the performance of the EDM process. Less attention has been given to modifying the electrical process parameters related to the pulse characteristics [18]. Md. Ashikur Rahman Khan et.al. studied the effect of various input parameters like pulse on time, pulse off time, peak current, gap voltage, and even the type of electrode material on the surface roughness of the machined Ti-5Al-2.5Sn. Three electrode materials were considered copper, copper tungsten, and graphite; it was found that at low discharge energy copper-tungsten electrode produces the best surface finish whereas graphite electrode produces the worst surface finish [19].

L.Tang and Y.F. Guo made the use of grey relation analysis and orthogonal design of experiments to optimize the machining parameters for EDM of novel S03 stainless steel. The most influencing parameter was peak current followed by pulse on time and then gap voltage [20].

Mehrdad Hosseini Kalajahi et.al. did a comparative study between the finite element analysis and experimental study of EDM on AISI H13 tool steel. It was found that an increase in current, voltage, and duty cycle had a positive effect on the material removal rate. Whereas when the pulse on-time is increased the Material removal rate increases up to a certain point and then decreases [21]. S.P. Sivapirakasam et.al. proposed a hybrid approach for multi-criteria decision making for EDM which consisted of Taguchi and fuzzy TOPSIS. A high carbon high chromium tool steel material was machined using a copper electrode. It was determined that the proposed method to optimize for green manufacturing was less complex and optimization was achieved with very little effort [22]. Serafim Opricovic and Gwo-HshiungTzeng did a comparative study between two multi-criteria decision making (MCDM) techniques namely VIKOR and TOPSIS. In the TOPSIS method, ideal solution is considered as two points but the method does not consider the relative distance of the solution from these two points whereas in VIKOR the closeness to the ideal condition is considered to rank the outcomes [23].

II. WORKPIECE AND TOOL PREPARATION

AISI D3 tool steel has been used as the workpiece material and the tool selected for this work is electrolytic copper. The AISI D3 was procured in the form of hot rolled round bars of diameter 25mm and a total length of 1500mm. The round bars were cut to a thickness of 20mm and a total of 54 pieces were made. The electrolytic copper electrode was procured in the form of flats of thickness 10mm and length 50mm. The workpiece was turned and faced using a manual lathe to the dimensions of 24mm diameter and 20 mm thickness. The copper electrode was machined using a vertical milling machine to the dimensions of 9.7 mm thickness and 50 mm length. The machined workpiece and electrode are presented in Fig 1,

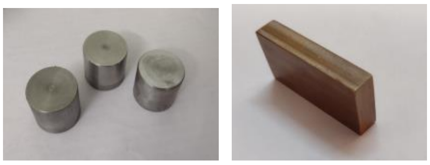

Fig 1: Workpiece and copper electrode before machining

After the workpiece was machined one sample was taken to check the hardness of the material. Vickers hardness test was used, since this is hardened steel a diamond indenter was used and a load of 150kg was applied on the sample. The Vickers hardness test gave a hardness value of 54HRC which confirms that this was hardened AISI D3 steel.

III. EXPERIMENTATION

The machining was carried out on Ratnaparkhi ENC series – EDM 5530 die-sinking EDM machine. The specification of the machine is given in Table 1.

Table 1: EDM machine specification

Maximum working current	35 A
Maximum working voltage	220 V
Range of pulse on time	1 to 99 μs
Range of pulse off time	1 to 9 μs
Length	2175 mm
Breadth	2150 mm
Height	1650 mm

The AISI D3 blanks were purchased in an already hardened state. Based on literature four input parameters were taken to perform the machining, these parameters are Peak current (I_p), Gap voltage (V_{gap}), Pulse on time (T_{on}), and Pulse off time (T_{off}). In each parameter, three levels of values were considered as shown in Table 2,

Table 2: Input parameters

S.No	**Parameters**	**Levels**		
		Low	**Medium**	**High**
1.	Peak current (I_p) (A)	10	20	30
2.	Gap Voltage (V_{gap}) (V)	25	50	75
3.	Pulse on Time (T_{on}) (μs)	30	60	90
4.	Pulse off Time (T_{off}) (μs)	3	6	9

The Design of Experiments (DoE) was done using Response Surface Methodology (RSM) Box Behnken design. As there are four factors and three levels a response surface design of 27 trials was chosen [25, 26]. Each experimental trial is done twice to ensure stability in the results.

Table 3 : DoE design matrix

S.No	**I_P (A)**	**T_{on} (μs)**	**T_{off} (μs)**	**V_{gap} (V)**
1	20	60	6	50
2	20	60	6	50
3	10	60	6	75
4	10	60	9	50
5	10	30	6	50
6	20	90	6	75
7	20	60	6	50
8	30	30	6	50
9	20	60	3	75
10	30	90	6	50
11	20	30	6	75
12	20	90	9	50
13	20	90	3	50
14	20	30	9	50

15	30	60	9	50
16	30	60	6	25
17	20	60	9	25
18	10	60	6	25
19	10	60	3	50
20	10	90	6	50
21	20	60	3	25
22	20	30	6	25
23	20	60	9	75
24	30	60	6	75
25	30	60	3	50
26	20	90	6	25
27	20	30	3	50

The four responses considered are Material Removal Rate (MRR), Surface roughness (Ra), Overcut (OC), and Parallelism. The MRR is calculated by the below formula,

$$\text{MRR} = \frac{\text{Weight before machining} - \text{Weight after machnining}}{\text{Time taken to perform machining}} \quad \text{(g/min)}$$

For this purpose, each of the 54 samples is weighed before machining and after machining as shown in Fig 2. The Surface roughness is measured using the Mitutoyo SJ-201 surface roughness tester. Overcut is nothing but the difference between the width of the tool used for machining and the width of the slot machined on the workpiece.

Overcut (OC) = Width of Slot machined – Width of the copper tool.

The parallelism of the slot is measured using the Mitutoyo Crysta Apex-S Coordinate Measuring Machine (CMM). This was done by creating two reference planes one for the top surface of the sample and one plane for the machined surface and the difference between the parallelism of these two planes is measured.

Fig 2: Weighing of samples before and after machining

Fig 3: EDM machine and machining

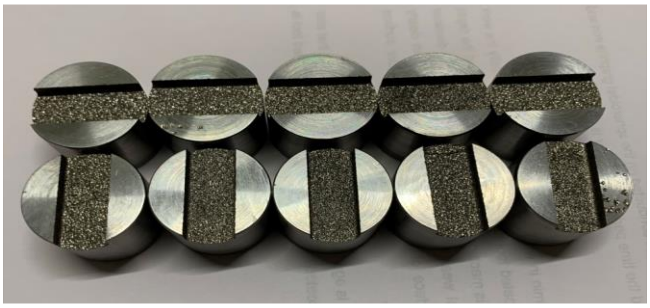

Fig 4: Sample of machined work pieces

IV. Results and Discussion

After the experiments were done the surface roughness, overcut and parallelism were measured using the surface roughness tester and the CMM. The MRR was also calculated using the formula given above. The results of the response variables are given in the Table 4,

Table 4: Response parameters

S.No	MRR (g/min)	R_a (μ)	Overcut (mm)	Parallelism (mm)
1	0.4373	24.185	0.3745	0.0825
2	0.4642	21.985	0.3885	0.084
3	0.1876	19.145	0.3315	0.1255
4	0.3066	19.595	0.3155	0.083

5	0.3224	14.61	0.268	0.0425
6	0.2889	25.365	0.411	0.1355
7	0.4651	24.555	0.3695	0.0855
8	0.6550	17.87	0.2815	0.2605
9	0.3095	25.02	0.335	0.2375
10	0.5044	27.3	0.5025	0.1225
11	0.3985	16.79	0.2895	0.168
12	0.4508	26.24	0.4125	0.1535
13	0.3696	24.08	0.406	0.132
14	0.7507	17.605	0.295	0.0735
15	0.6893	25.675	0.3925	0.076
16	0.6191	31.74	0.357	0.05
17	0.6376	21.335	0.339	0.1025
18	0.4450	20.1	0.289	0.113
19	0.2503	21.18	0.315	0.075
20	0.8156	21.045	0.342	0.0805
21	0.5661	25.24	0.3315	0.1015
22	0.6942	19.54	0.257	0.048
23	0.3653	24.56	0.384	0.05
24	0.4524	27.605	0.3955	0.07
25	0.5685	28.13	0.382	0.0785
26	0.4924	30.15	0.4055	0.0715
27	0.4344	15.865	0.255	0.069

VIKOR method:

This method is one among the multi- criteria decision-making techniques used to find the optimized set of parameters [27]. The steps for this method are given below.

Step1: Assign the weights denoting the importance of the response variables.

Step 2: Identify beneficial and non-beneficial criteria, i.e. the criteria for which lower values are desired are called non-beneficial criteria's and those whose higher value is desired are called beneficial criteria.

Step 3: Find best and worst values for beneficial and non-beneficial criteria. Best is the max value for beneficial criteria and min value for non-beneficial criteria. The worst is min value for beneficial criteria and the max value for non-beneficial criteria.

Step 4: Calculate unity measure (Si).

$$S_i = \sum_{j=1}^{n} w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)}; \quad i = 1, \ldots, m$$

Step 5: Calculate individual regret (Ri).

$$R_i = \max_j \left[w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right]; \quad i = 1, \ldots, m, \ j = 1, \ldots, n$$

Step 6: Find, S^* = min Si ; S^- = max Si ; R^* = min Ri ; R^- = max Ri . Calculate Qi for each row in which U=0.5.

$$Q_i = \upsilon \left[(S_i - S^*) / (S^- - S^*)\right] + (1- \upsilon) \left[(R_i - R^*) / (R^- - R^*)\right]$$

Step 7: Based on the values of Q_i ranking is done the lowest value is given the first rank.

Step 8: To finalize the optimized value two checks need to be done,

C1 = Acceptable advantage and C2 = Acceptable stability in decision making.

For C1 the below condition needs to be satisfied,

$Q(A^2) - Q(A^1) \geq DQ$

Where DQ = 1/(j-1), j is given by the number of trials. For C2 the condition is the trial that ranks first according to the Q_i value needs to rank first either according to the corresponding S_i or R_i values.

If any of the above conditions fail the C2 check is done for the lower-ranked values starting from rank 2 and ranks 3 trials and is repeated till it satisfies the condition. At that point, the pair of values is taken as the optimized solution. The ranks of the corresponding trials are given in Table 5.

Table 5: VIKOR ranking

S.No	Rank (Based on Qi)	Rank (Based on Ri)	Rank (Based on Si)
1	17	17	16
2	12	13	14
3	27	27	25
4	22	24	17
5	16	22	8
6	26	25	27
7	13	12	15
8	4	4	4
9	25	23	26
10	19	10	24
11	14	19	12
12	20	15	22
13	23	20	23
14	1	1	1
15	6	5	7
16	8	9	11
17	5	6	5
18	11	16	10
19	24	26	21
20	2	2	3
21	7	8	9
22	3	3	2
23	21	21	20
24	18	14	18
25	10	7	13
26	15	11	19
27	9	18	6

SEM analysis:

Further in this study SEM analysis [24] was done on different input parameter samples, the images of which are given in Figs 5,6,7 & 8. Machining defects such as ridge-rich surfaces, micro-voids, and micro-cracks are part of the surface microgeometry characteristics. Material melted during EDM generated the ridge-rich surface, which was then blasted out of the surface by the discharge pressure. The surface, on the other hand, quickly achieved the solidification temperature when the working fluid-cooled it. Gas bubbles ejected from the molten material during solidification are responsible for the micro-voids. Thermal strains caused micro-cracks to form. The rapid heating and cooling rate, as well as the non-uniform temperature distribution, were the main causes of residual stress in the machined surface. Furthermore, the EDM surface's shape was influenced by the discharge energy used. The surface characteristic displays changing hillocks and troughs when varying pulsed current and pulse-on duration are used. Deeper cracks or voids, as well as more prominent flaws, are visible in the pulsed current and pulse-on duration variation.

Fig 5. shows the SEM images of the surface machined using a lower parameter setting. The parameters used are peak current 10amps, pulse on duration 30µs and pulse off duration 3µs and, gap voltage 25v. It can be inferred that the surface consists of shallow voids and crests sparked during machining.

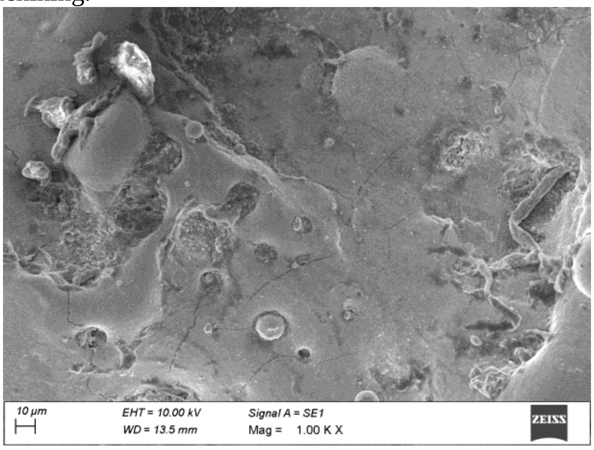

Fig 5: SEM image of machined surface at low parameter setting

Fig 6. shows the SEM images of the surface machined using a medium parameter setting. The parameters used are peak current 20amps, pulse on duration 60µs and pulse off duration 6µs and, gap voltage 50v. The surface consists of dense voids and crests sparked during machining when compared with the surface obtained using minimum level process parameters.

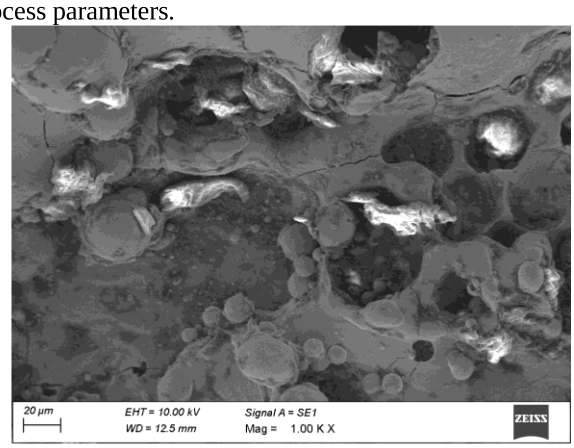

Fig 7. shows the SEM images of the surface machined using a higher level parameter setting. The parameters used are peak current 30amps, pulse on duration 90µs and pulse off duration 9µs and, gap voltage 75v. The surface consists of course voids and crests sparked during machining. The topography reveals the presence of grey areas which shows heavy burning of the surface irrespective of the rapid cooling by the dielectric medium.

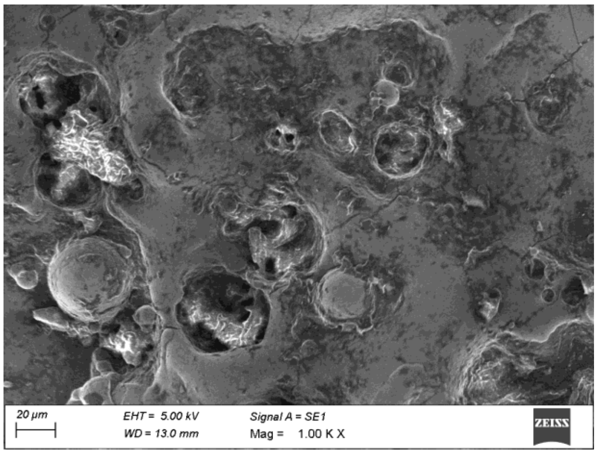

Fig 8: SEM image of machined surface at high parameter setting

Fig 8. shows the SEM images of the surface machined using an optimum parameter setting. The parameters used are peak current 20amps, pulse on duration 30µs and pulse off duration 9µs and, gap voltage 50v. The surface consists of a few shallow voids and crests when compared with surface machined using other parameter settings. The surface was found to be smooth with better topography.

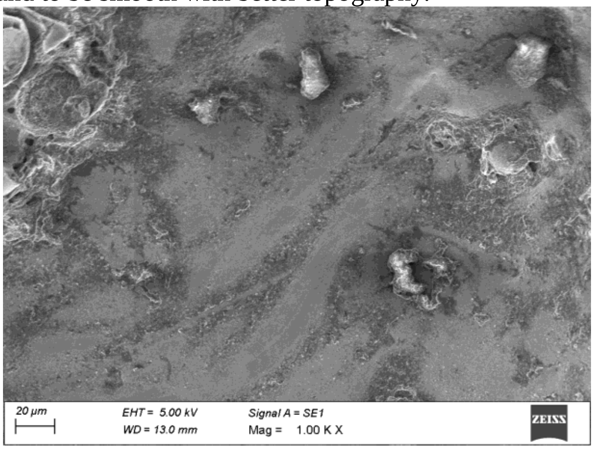

Fig 8: SEM image of machined surface at optimized parameter setting

Higher pulsed current and longer pulse-on duration cause a poorer surface finish. This is because a greater pulsed current and longer pulse-on duration may generate more frequent dielectric fluid cracking, as well as more frequent melt expulsion, resulting in deeper and wider craters on the workpiece's surface**.** In comparison to the SEM results, it is evident that excellent surface topography was obtained on the machined surface using the identified optimal parameter setting. The effect of optimum parameter combination is also well-established using confirmation trials.

V. CONCLUSION

Based on the experiments and the optimization done using the VIKOR method the conclusion is that, the optimized parameter found are I_p= 20A, V_{gap}=50V, T_{on}=30µs, and T_{off} = 9µs. The SEM images also prove that the surface machined using these set of parameters had better surface characteristics with no cracks and very little recast. It was also found that the VIKOR method gives an optimized solution with very few calculations compared to other MCDM techniques. For the responses, MRR, Overcut, and Surface roughness Peak current, and Pulse on time were found to be the most influencing parameters whereas for parallelism Peak current and gap voltage were found to be the most influencing parameters.

ACKNOWLEDGMENT

The authors wish to sincerely thank the management and principal of PSG College of Technology, Coimbatore for providing infrastructure and other facilities to carry out this work.

REFERENCES

[1] Alla M.Ubaid, ShukryH.Aghdeab, Ahmed Ghazi Abdulameer, LAith Abdullah Al-Juboori and Fikri T.Dweiri, "Multidimensional optimization of electrical discharge machining for high speed steel (AISI M2) using Taguchi- fuzzy approach" International Journal of System assurance Engineering management, January 2020

[2] Ali Kalyon, "Optimization of machining parameters in sinking electrical discharge machine of caldie plastic mold tool steel", Sadhana (Indian academy of science), January 2020.

[3] Vikas K.Shukla, Rakesh Kumar and Bipin Kumar Singh, " Evaluation of machining performance and multi criteria optimization of novel metal-Nimonic 80A using EDM", December 2020.

[4] Sudhir Kumar, Sanjoy Kumar Ghoshal, Pawan Kumar Arora and Leeladhar Nagdeve, "Multi-variable optimization in die-sinking EDM process of AISI420 stainless steel", Materials and manufacturing processes, November 2020.

[5] B. Singaravel, S.Deva Prasad, K.Chandra Shekar, K.Mangapathi Rao and G.Gowtham Reddy,"Optimization of process parameters using hybrid Taguchi and VIKOR method in electrical discharge machining process", Advanced Engineering Optimization through intelligent techniques, Advances in Intelligent Systems and Computing, November 2020.

[6] Phan Nguyen Huu, Long Banh Tien, Quy Tran Duc, Dong Pham Van, Chung Nguyen Xuan, Thien Nguyen Van, Luan Nguyen Duc, Muhammad Jamil and Aqib Mashood Kha,"Multi-objective optimization of process parameter in EDM using low-frequency vibration of work piece assigned for SKD61", Sadhana (Indian Academy of Sciences), July 2019.

[7] T.R. Paul, A.Saha, H. Majumder, V.Dey and P.Dutta,"Multi-objective optimization of some correlated process parameters in EDM on Inconel 800 using a hybrid approach", Journal of the Brazilian Society of Mechanical Science and Engineering, June 2019.

[8] Nishant K.Singh, Yashvir Singh, Sanjeev Kumar and Abhishek Sharma, " Comparative study of statistical and soft computing-based predictive models for material removal rate and surface roughness during helium-assisted EDM of D3 die steel", SN Applied Sciences, May 2019.

[9] Tiago Czelusniak, Camila Fernandes Higa, Ricardo Diego Torres, Carlos Augusto Henning Laurindo, Jose Mario Fernandes de Pavia Junior, Armin Lohrengel and Fred Lacerda Amorim, "Materials used for sinking EDM electrodes: a review", December 2018.

[10] L'uboslav Straka and Slavomira Hasova,"Optimization of material removal rate and tool wear rate of Cu electrode in die-sinking EDM of tool steel", The International Journal of Advanced Manufacturing Technology, May 2018.

[11] Mohammadjafar Hadad, Lan Quang Bui and Cong Thanh Nguyen, "Experimental investigation of the effects of tool initial surface roughness on the electrical discharge machining (EDM) performance", The International Journal of Advanced Manufacturing Technology, November 2018.

[12] Uttam Kumar Mohanty, Jaydev Rana and Abhay Sharma," Multi-objective optimization of electro-discharge machining (EDM) parameter for sustainable machining", Materials Today: Proceedings, January 2017.

[13] S.Vinoth Kumar and M.Pradeep Kumar,"Experimental investigation and optimization of machining process parameters in AISI D2 steel under conventional EDM and Cryogenically cooled EDM process", Transactions of the Indian Institute of Metals, March 2017.

[14] Muhammet Gul, Erkan Celik, Nezir Aydin , Alev Taskin Gumus and Ali Fuat Guneri,"A state of the art literature review of VIKOR and its fuzzy extensions", Applied Soft Computing, May 2016.

[15] R. Manivanan and M. Pradeep Kumar,"Multi-response optimization of Micro-EDM process parameters on AISI304 steel using TOPSIS", Journal of Mechanical Science and Technology, January 2016.

[16] Shailesh Dewangan, Soumya Gangopadhyay and Chandan Kumar Biswas," Multi-response optimization of surface integrity characteristics of EDM process using grey-fuzzy logic based hybrid approach", Engineering Science and technology, an International Journal, March 2015.

[17] S. Dewangan, S. Gangopadhyaya and C.K. Biswas, "Study of Surface Integrity and Dimensional Accuracy in EDM using fuzzy TOPSIS and Sensitivity analysis", Measurement, January 2015.

[18] T. Muthuramalingam and B. Mohan,"A review of influence of electrical process parameters in EDM process", Archives of civil and mechanical engineering, March 2015.

[19] Md.Ashikur Rahman Khan, M.M. Rahman and K.Kadrigama,"An experimental investigation on surface finish in die-sinking EDM of Ti-5Al-2.5Sn", International Journal of Advanced Manufacturing Technology, March 2015.

[20] L. Tang and Y.F. Guo,"Electrical discharge precision machining parameters optimization investigation on S-03 special stainless steel", International Journal of Advanced Manufacturing Technology, October 2013.

[21] Mehrdad Hosseini Kalajahi, Samrand Rash Ahmadi and Samad Nadimi Bavil Oliaei,"Experimental and finite element analysis of EDM process and investigation of material removal rate by response surface methodology",

International Journal of Advanced Manufacturing Technology, May 2013.
[22] S.P. Sivaprakasam, Jose Mathew and M. Surianarayanan,"Multi-attribute decision making for green electrical discharge machining", Expert Systems with Applications, June 2011.
[23] Serafin Opricovic and Gwo-Hshiung Tzeng,"Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS", European Journal of Operational Research, December 2004.
[24] Somasundaram, M., and J. Pradeep Kumar. "Effect of Process Parameters in Electric Discharge Machining of AZ31 Magnesium Alloy." Trends in Manufacturing and Engineering Management (2021): 3-13.
[25] Somasundaram, M., J. Pradeep Kumar and M. Mathan. "Investigation on surface Integrity, Machining and Form tolerance characteristics using TOPSIS approach for Electrical Discharge Machining of Biocompatible material." Materials Today: Proceedings 22 (2020): 1853-1860.
[26] Jeyaraj, Pradeep Kumar. "Process Robustness and Effect of Process Parameters on Rapid Joining of Electrical Contacts by Ultrasonic Vibrations." Jordan Journal of Mechanical & Industrial Engineering 13.4 (2019).
[27] Kumar, RS Nandha, and J. Pradeep Kumar. "Experimental Investigation on the Effects of Welding Parameters in Tungsten Inert Gas Welding of Hastelloy C-276." Materials, Design, and Manufacturing for Sustainable Environment. Springer, Singapore, 2021. 397-407.