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ORIGINAL PAPER

Multi-criteria Decision-making of Vibration-aided Machining for High Silicon-carbon Tool Steelwith Taguchi–topsis Approach

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Abstract

The frequency-aided electrical erosion machining process can enhance the process mechanism and efficacy. It is time consuming to choose the optimal vibration-oriented parameters in the electrical discharge machining (EDM) process. In the present study, the technique for order of preference by similarity to ideal solution (TOPSIS) based multi-attribute optimization was proposed in the process on machining high silicon-carbon tool steel under low vibrational frequency of the workpiece material. The surface roughness, material removal rate, micro-hardness, and white layer thickness were chosen as quality measures. The experimental investigation was performed by comparing TOPSIS engineering optimization with Deng's approach, preference selection index, grey relational analysis, the Visekriterijumsko–Kompromisino–Rangiranje (VKR) approach, simple additive weighting, and complex proportional assessmentto analyse the accuracy of the TOPSIS approach. From the experimental analysis, it was inferred that the low-frequency vibration-associated workpiece can considerably improve the quality factors in EDM. The Taguchi–TOPSIS approach can provide a better computational approach to resolve the multi-objective optimal problem.

Keywords EDM · Optimization · Frequency · Vibration · Surface roughness · Material removal rate · Micro-hardness · White layer thickness

1 Introduction

The mechanism of the electrical discharge machining (EDM) process can be enhanced by incorporating vibration in the machining process [1–3]. The vibration can effectively remove the chip release to enhance the machining stability. It improves the productivity and the machining quality in the EDM process. As compared with traditional EDM, the better quality measures of the machining surface under vibrational frequency of 150 Hz assigned to the electrode in EDM for machining W9Mo2Cr4V alloy [4]. A lower overcut and taper angle were observed with high material removal in EDM. It was found that the machining time can contribute to modify the material removal rate (MRR) and (tool wear rate) TWR in EDM with vibration aided specimen. It could produce better MRR and lower TWR. Yu et al. [5] combined simulation and experimentation in the vibration-assisted EDM process to analyse particle removal in the machining zone. The EDM process mechanism can be enhanced by a dielectric medium, coated electrode, and incorporation [6–10]. The high amplitude and frequency of vibrations could affect machining efficiency in such processes because of the instability of the discharge generation. Vibration-assisted EDM can improve the processing of titanium materials considerably [11].The Box–Behnken design was utilized to analyze the correlation between quality criteria and process factors with low vibrational frequency[12]. The frequency assisted workpiece based EDM machining with a lower frequency of 280 Hz can provide a better surface quality [13].

The low frequency vibration can considerably improve the process mechanism by reducing the short-circuit pulse. The vibration applied to the solvent nozzle does not significantly affect the surface roughness[14]. The machining time in EDM with ultrasonic vibration was reduced compared with traditional EDM. The amplitude of frequency has a negligible effect on the measures in the EDM process. The ultrasonic

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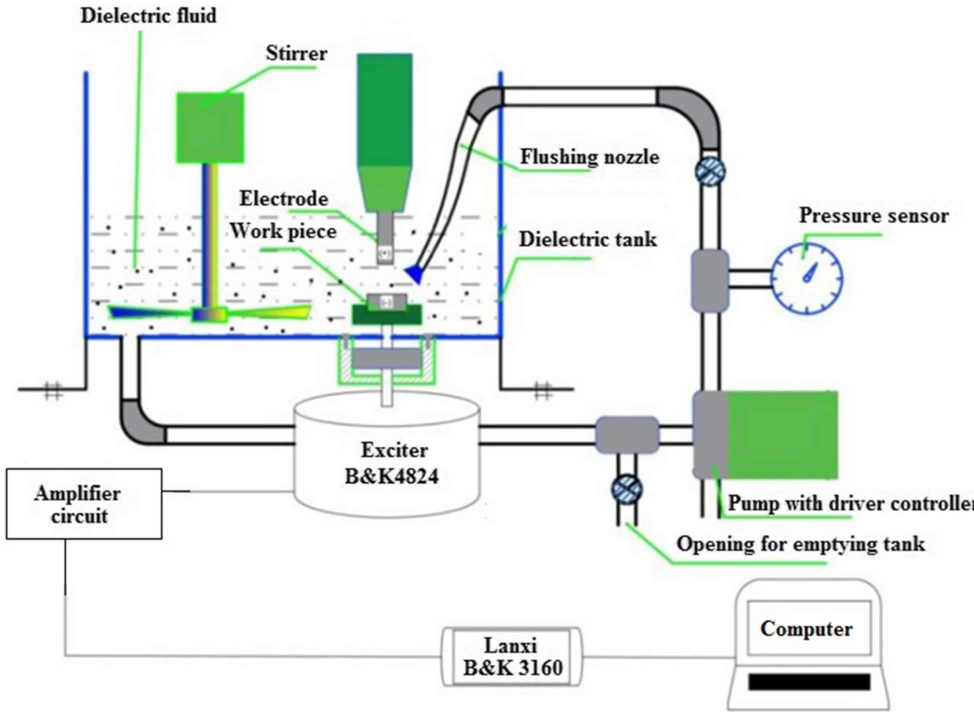


Fig. 1 The mechanism of the low frequency vibration in EDM process

Table 1 Chemical composition of silicon steel

Elements	C	Si	Cu	P	S	Mo	Mn	Cr	Ni	Al	Iron
Composition %	0.035	0.44	0.38	0.013	0.022	0.022	0.55	0.025	0.033	0.33	Balance

vibrations have a greater efficiency in μ-EDM than the low-frequency vibrations [15]. It is happened due to the effective utilization of vibrations by optimizing the process parameters. Many studies were performed to obtain optimal factors in EDM under vibration [16]. However, the selection of the optimal method, especially for multi-criteria decision making (MCDM), to solve the vibration-assisted process is time consuming [17].Many optimization techniques were introduced recently, and many MCDM methods have been used in the

Table 2 The levels of the process parameters

Levels	I (A)	T_{on} (μs)	T_{off} (μs)	F (Hz)
1	3	12	5.5	128
2	6	25	12.5	256
3	8	50	25	512

Table 3 Experimental matrix and observed EDM performance measures

Exp.No	I (A)	T_{on} (μs)	T_{off} (μs)	F (Hz)	MRR (mm^3/min)	R_a (μm)	HV (HV)	WLT (μm)
1.	3	12	5.5	128	2.333	2.22	704.980	3,629
2.	3	25	12.5	256	2.827	2.97	727.040	4,023
3.	3	50	25	512	3.564	2.19	802.600	4,284
4.	6	12	12.5	512	4.460	2.28	715.640	7,911
5.	6	25	25	128	3.154	3.72	786.540	7,430
6.	6	50	5.5	256	5.470	3.31	957.980	8,574
7.	8	12	25	256	5.855	4.17	888.480	15,334
8.	8	25	5.5	512	9.564	5.24	678.660	18,267
9.	8	50	12.5	128	5.205	5.07	744.680	14,308

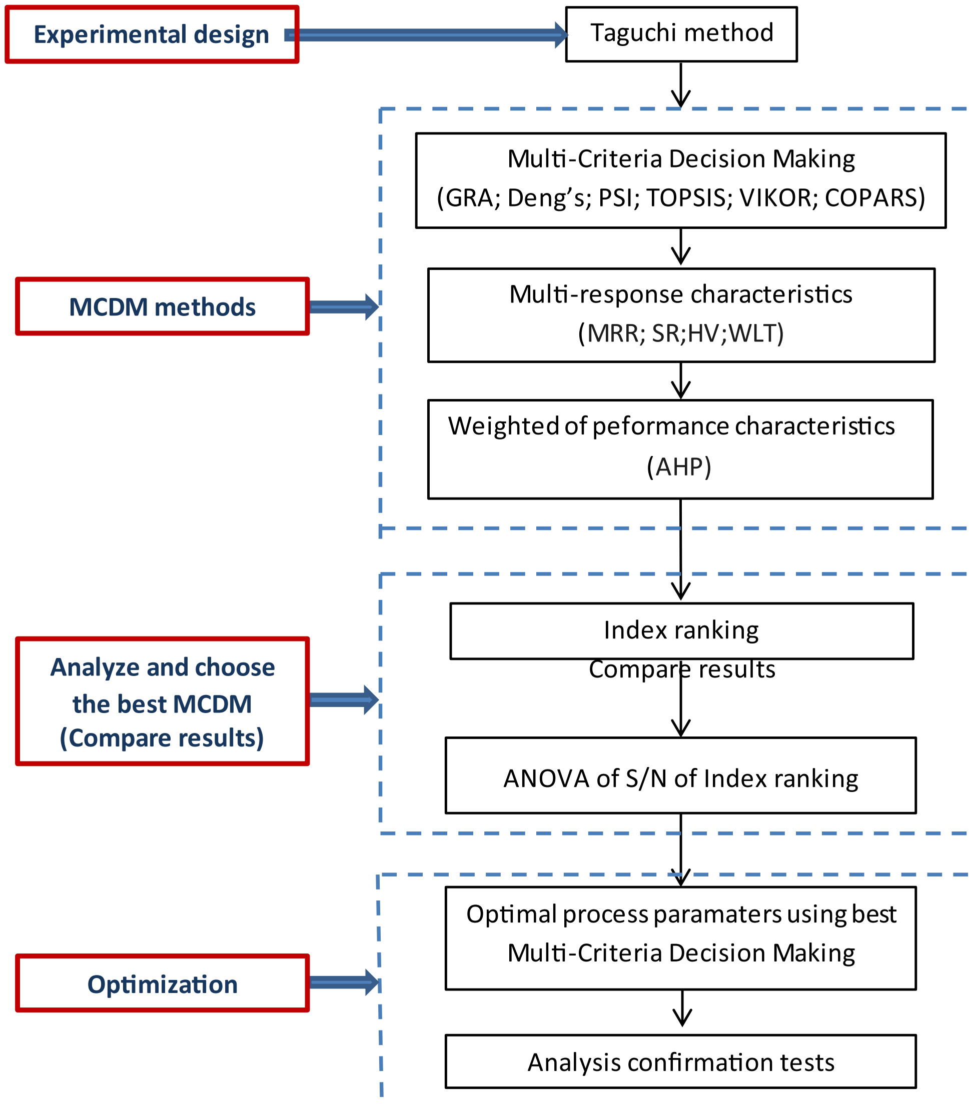


Fig. 2 The steps of the proposed methodology

machining process [18, 19]. Response surface methodologies (RSMs) can also be used in many EDM applications. However, RSM has several issues, such as handling non-linearity, the need for higher interpretation knowledge and a large number of input parameters. Some advanced methods, such as neural networks can provide greater promise as cited in the literature [20–22]. Grey based relational analysis (GRA) and TOPSIS are the most commonly used methods in this field [23]. It was compared the effectiveness of TOPSIS for the multi goal decision method in the machining process [24]. It was found that TOPSIS was a promising MCDM method in the field of EDM. In multi objective optimization, determining the weight of quality indicators is important[25]. Hence, TOPSIS is suitable for the EDM process with vibration owing to its adaptability [26].

In previous studies, only a few research considerations were provided to improve the mechanism in the vibration-assisted process by implementing MCDM approaches. Hence, in this investigation, an endeavour was made to optimize the factors in the vibration-aided material removal to implement the TOPSIS approach for machining high silicon-carbon tool steel. The suitability of the MCDM method used in the analysis was also assessed through comparison with several methods: Deng's approach, preference selection index (PSI), complex-proportional-assessment (COPRAS), GRA, simple-additive-weighting (SAW), and VIKOR approach [27–29].

2 Materials and Methods

The machining process can be enhanced through proper de-ionization of the insulating medium inthe machining zone after every discharge. In the conventional machining process,

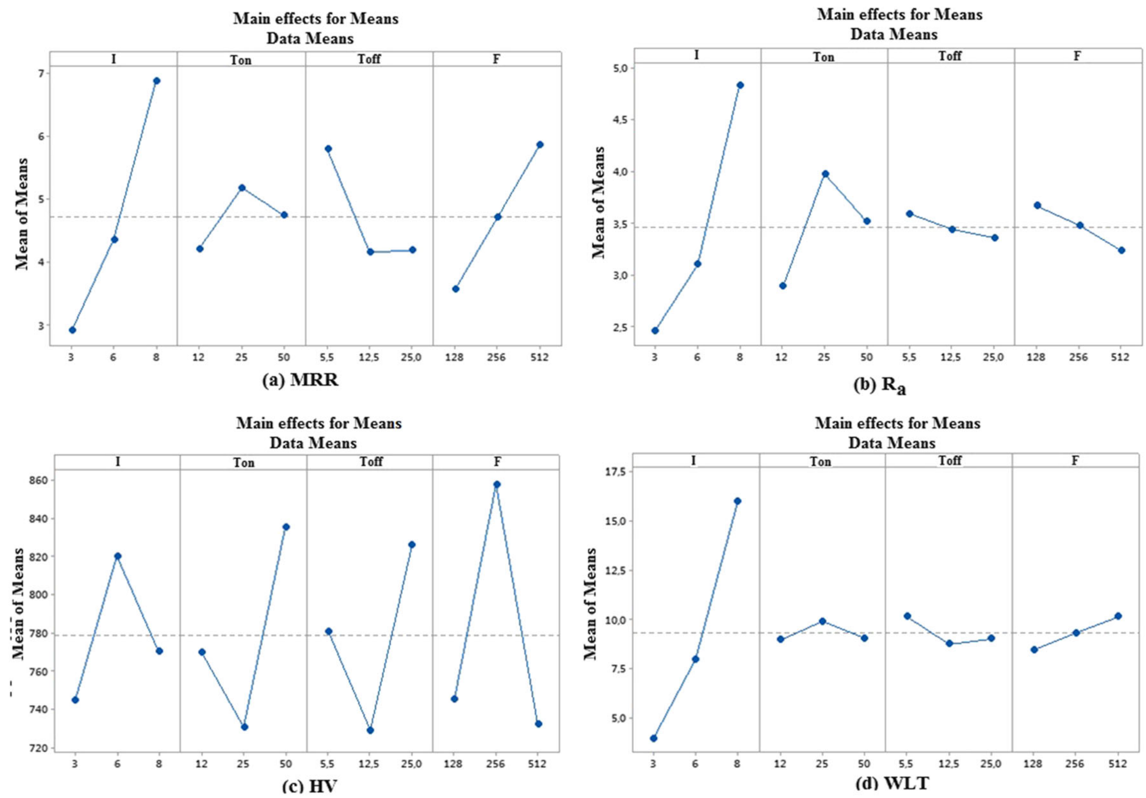


Fig. 3 The influence of process parameters on quality indicators

a flushing process through controlled fluid flow in the machining zone performs deionization. However, an improvement is still needed in the flushing process. The low-frequency ultrasonic sound waves connected to the workpiece, as shown in Fig. 1, can increase the possibility of removing the machined particles efficiently. Hence, the proposed approach can improve the performance measures of the process with better surface quality. A CM323C machine (from CHMER-Taiwan) was utilized for the machining experiments. The voltage (U), current (I), pulse-on-time (T_{on}), frequency (F) and pulse-off-time (T_{off}) were chosen as input factors for the present study. High silicon-carbon tool steel was chosen as specimen material of 25 × 25 × 30 mm. The chemical composition of silicon steel is shown in Table 1 [30]. The copper (Cu)

Table 4 Prediction accuracy for the single response optimization

No	quality indicators	Optimization processes parameters	Optimal responses value		Percentage difference
			Calculated	Experimental	
1	MRR (mm^3/min)	I = 8A; T_{on} = 50 μs; T_{off} = 5.5 μs; F = 512 Hz	9.129	9.765	6.90
2	R_a (μm)	I = 3A; T_{on} = 12 μs T_{off} = 5.5 μs; F = 512 Hz	2.05	2.19	6.82
3	HV (HV)	I = 6A; T_{on} = 50 μs T_{off} = 25 μs; F = 256 Hz	853.7	797.29	6.57
4	WLT (μm)	I = 3 A; T_{on} = 12 μs T_{off} = 12.5 μs; F = 128 Hz	2.35	2.59	10.21

Table 5 Calculation results by various multi-objective methods

Exp. No	MRR (mm^3/min)	R_a (μm)	HV (HV)	WLT (μm)	GRA		Deng's		PSI		TOPSIS		VIKOR		COPARS	
					Z_j	Rank	P_i	Rank	C_i	Rank	P_i	Rank	P_i	Rank	Q_j	Rank
1	2.333	2.22	704.98	3.629	0.115	7	0.384	6	0.277	6	0.344	7	0.372	4	0.114	4
2	2.827	2.97	727.04	4.023	0.130	4	0.376	7	0.313	4	0.321	8	0.350	3	0.103	7
3	3.564	2.19	802.60	4.284	0.105	8	0.433	3	0.351	1	0.397	5	0.615	5	0.123	2
4	4.460	2.28	715.64	7.911	0.095	9	0.443	1	0.317	3	0.438	4	0.802	9	0.121	3
5	3.154	3.72	786.54	7.430	0.158	2	0.357	9	0.284	5	0.267	9	0.223	1	0.089	9
6	5.470	3.31	957.98	8.574	0.127	5	0.431	4	0.332	2	0.479	2	0.745	8	0.114	5
7	5.855	4.17	888.48	15.334	0.155	3	0.403	5	0.269	7	0.447	3	0.626	6	0.104	6
8	9.564	5.24	678.66	18.267	0.116	6	0.439	2	0.192	9	0.656	1	0.666	7	0.138	1
9	5.205	5.07	744.68	14.308	0.175	1	0.373	8	0.242	8	0.350	6	0.336	2	0.095	8

*Weight of quality criterias: W_{MRR}=0.45; W_{Ra}=0.321; W_{HV}=0.087; W_{WLT}=0.142

electrode material was considered as the tool electrode with D323 oil as a insulating fluid with the Exciter 4824 model vibration unit (Brüel&Kjær, Denmark), as shown in Fig. 1. The vibrating head ensures that the vibration rate is assigned to the workpiece for accurate machining. The selected process factors in the study are tabulated in Table 2, along with their levels based on low, medium and higher values of available range of parameters setting.

The Performance measures, including the material removal rate (MRR), surface roughness (R_a), microhardness (HV) and white layer thickness (WLT) were considered for this investigation to examine the efficacy of the optimal problem in vibration-assisted EDM. The average WLT was computed using the method reported by Muthuramalingam [30]. The weight of the specimen was measured using Shinko-Denshi AJ-203 digital electronic balance with an accuracy of 0.001 g. The R_a was computed using an SV-1200 surf-corder (Mitutoyo, Japan). The HV was calculated using an Indenta Met-1106 micro hardness tester (from Buehler, USA). The surface morphology of the layer was acquired using an Axiovert-40MAT microscope (Carl Zeiss, Germany).The MRR and HV values were considered as higher-better quality characteristics in the present study. The R_a and WLT values were chosen as lower-better quality measures for experimental investigation.

The Taguchi method is an experimental matrix in the vibration-assisted EDM process to reduce the experimental cost. The experimental matrix and results of the study are shown in Table 3. This method must be combined with a MCDM method, such as the TOPSIS, GRA, MCDM on-the-basis-of-Ratio Analysis (MOORA), and Data-Envelopment-Analysis-Based-Ranking (DEAR) methods, for better prediction. Hence, the Taguchi method was combined with various multi-goal decision algorithms. The steps for solving the MCDM based problem of the present study were performed to optimize the accuracy of the results as depicted in Fig. 2.

3 Results and Discussion

The significance of factors on quality factors in the vibration-assisted EDM is discussed in this section. The variation of the output line from the mean line indicates the most effect on the performance measures in the EDM process. The plots of the main effects were obtained using the Minitab software package. Figure 3a shows that I and F possess a higher significance on the MRR. I = 3–8A and F = 126–512 Hz led to larger MRR with higher I and F. A 136.4% higher MRR was observed with I = 8A and F = 512 Hz. This is due to the higher current, which can lead to higher discharge energy. Hence, the amount of molten material has also been increased. The higher frequency has resulted in easy removal of chip from discharge gap. Then, the insulating fluid in the machining zone could be replaced to increase the stability of the machining processes. A higher F also increased the number of sparks to improve the MRR. The change in T_{on} and T_{off} can affect the discharge energy for restoring the dielectric fluid and eject the chip elements from the discharge gap. These effects have a direct impact on material ejection and the constancy of the EDM machining process. However, the effects of T_{on} and T_{off} on the MRR in EDM with vibration are negligible compared with I and F. The effects of I, T_{on}, and T_{off} on R_a were found to be similar to their influence on the MRR, as shown in Fig. 3b. This is owing to the higher discharge energy

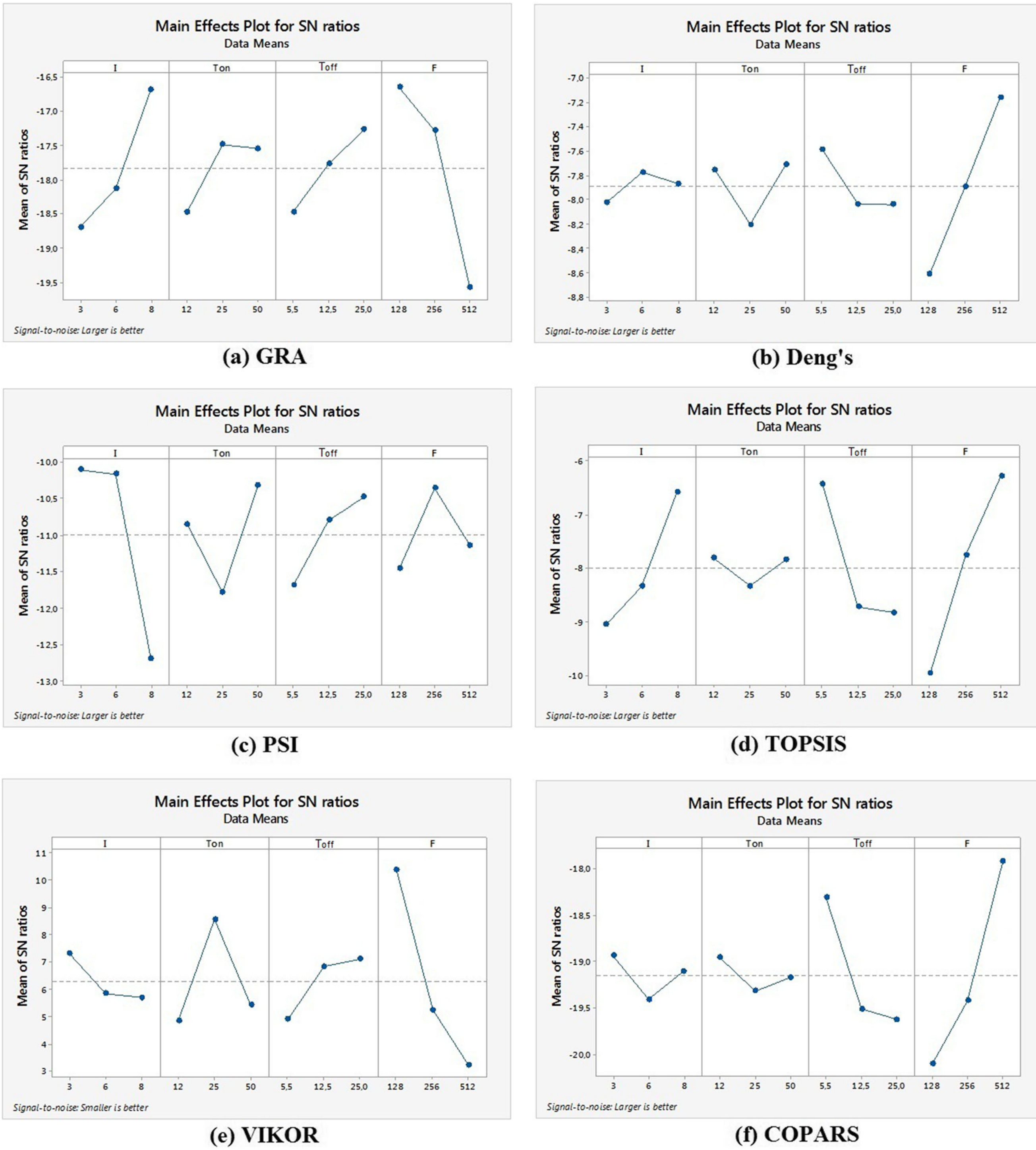


Fig. 4 S/N ratio plot for optimal setting of process parameters

under higher I and T_{on}, which led to a larger crater diameter and depth. Because of this instability during the formation of sparks, surface roughness values were affected. The number of sparks increased with higher F, leading to a reduction in the energy of each spark and the size of the craters.

As Fig. 3c shows, the effects of I and F on the HV were quite similar. The HV was the largest at I = 6A and F = 256 Hz, and the HV was the smallest at I = 3A and F = 512 Hz. The change of HV resulted from the change in elemental composition and structure of the surface layer. The WLT was formed on the surface owing to the resolidified

Table 6 Compare the effectiveness of methods with the first experiment

Method	Exp. No.1	Best exp.	Improvement (%)
GRA	0.115	0.175	52.2
Deng's	0.384	0.443	15.4
PSI	0.2774	0.3512	26.6
TOPSIS	0.344	0.656	90.7
VIKOR	0.372	0.223	40.1
COPARS	0.114	0.138	21.1

improve the workpiece properties, the smaller-the-better characteristics must be chosen for the WLT. Figure 3d shows that higher I and F can lead to higher WLT. Table 4 shows the consolidated single-response optimized parameters using the main effects plot, along with the prediction accuracy. A higher I can increase the spark discharge energy, which can affect the pulse temperature of the workpiece for higher WLT. The higher F can increase the WLT owing to the importance of F for the amount of debris being pushed out across the machining gap. The weight (W) of the quality criteria was decided by the analytical process method [25], and the weights of the quality factors included W_{MRR} = 0.45, W_{SR} = 0.321, W_{HV} = 0.087, and W_{WLT} = 0.142. Table 5 shows the estimation of optimal process factors using the GRA, Deng, PSI, TOPSIS,

Table 7 The change of the optimal results compared with results of the best experiment

Multi-objective optimization method		Optimal Machining conditions	Different parameters	Measures			
				MRR	R_a	HV	WLT
GRA	Best exp.	I = 8A; T_{on} = 50 µs; T_{off} = 12.5 µs; F = 128 Hz	T_{on}, T_{off}	5.205	5.07	744.68	14.30
	S/N	I = 8A; T_{on} = 25 µs; T_{off} = 25 µs; F = 128 Hz		1.701	3.07	711.36	3.43
	% change			67.3 Decrease	39.3	4.5	76.0
Deng's	Best exp.	I = 6A; T_{on} = 12 µs; T_{off} = 12.5 µs; F = 512 Hz	T_{on}, T_{off}	4.460	2.28	715.64	7.91
	S/N	I = 6A; T_{on} = 50 µs T_{off} = 5.5 µs; F = 512 Hz		6.615	3.06	832.44	9.418
	% change			48.3 Increase	34.4	16.3	19.0
PSI	Best exp.	I = 3A; T_{on} = 50 µs; T_{off} = 25 µs; F = 512 Hz	F, T_{off}	3.564	2.19	802.60	4.284
	S/N	I = 3A; T_{on} = 50 µs; T_{off} = 25 µs; F = 256 Hz		2.42	2.44	928.13	3.44
	% change			32.1 Decrease	11.3 Increase	15.6	19.7 Decrease
TOPSIS	Best exp.	I = 8A; T_{on} = 25 µs; T_{off} = 5.5 µs; F = 512 Hz	T_{on}	9.564	5.24	678.66	18.267
	S/N	I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 512 Hz		9.87	4.79	683.00	17.42
	% change			3.2 Increase	-8.7 Decrease	0.6 Increase	-4.7 Decrease
VIKOR	Best exp.	I = 6A; T_{on} = 25 µs; T_{off} = 25 µs; F = 128 Hz	I	3.154	3.72	786.540	7.430
	S/N	I = 3A; T_{on} = 25 µs; T_{off} = 25 µs; F = 128 Hz		1.701	3.07	711.360	3.437
	% change			-46.1 Decrease	-17.3	-9.6	-53.7
COPARS	Best exp.	I = 8A; T_{on} = 25 µs; T_{off} = 5.5 µs; F = 512 Hz	T_{on}, I	9.564	5.24	678.660	18.267
	S/N	I = 3A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 512 Hz		4.632	1.78	691.880	5.327
	% change			-51.6 Decrease	-65.9	1.9 Increase	-70.8 Decrease

specimen and tool electrode material by dielectric fluid. Because the thickness of the recast layer must be reduced to VIKOR, and COPRAS methods for MCDM. The optimal findings from the MCDM approach by TOPSIS were found

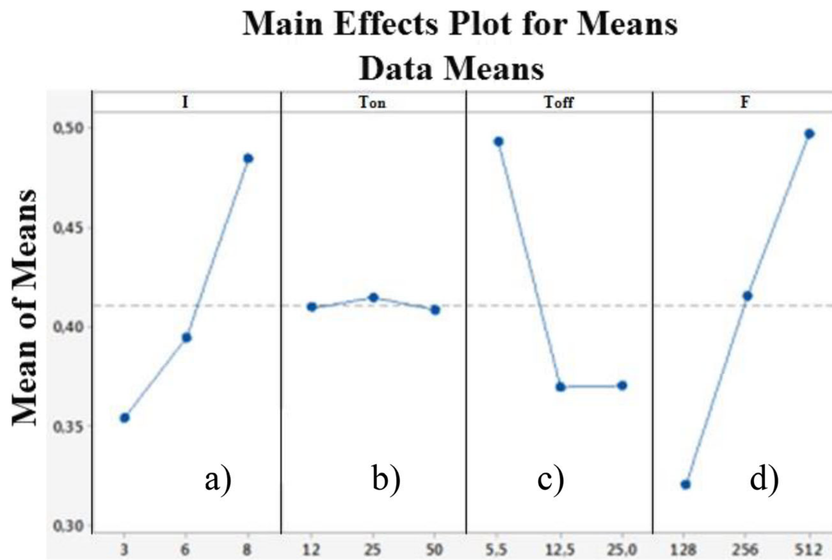


Fig. 5 The influence of process parameters to Topsis-C_i

using the eighth trial for optimal process parameter computation. The PSI approach used the third trial as the optimal combination. Nevertheless using Deng's method,the fourth trial was inferredas the optimal combination. For the VIKOR method computation,the fifth trial produced better quality measures in the process.

There are many difficulties on choosing a multi-goal decision method because different MCDM approach may provide different results. Hence, a comparison of the results between methods to select the most reasonable one is important. In this study, the effectiveness of each solution was evaluated in the EDM multi-objective decision, as shown in Table 6. In the investigation, the TOPSIS efficiency in EDM with low-frequency vibration was observed to be high. Hence, TOPSIS is the most suitable method among the methods studied owing to its higher accuracy. The optimal set of parameters was computed by the Taguchi signal-to-noise (S/N) analysis, Fig. 4. The optimum set of parameters and optimal results were determined, as shown in Table 7. This led to the quality indicators determined by S/N analysis being different from those of the best experiment. The results of the quality criteria are shown in Table 7. The TOPSIS and VIKOR approaches could differ in the number of factors between the best experiment and the optimal process parameters by S/N analysis is the least. The results of the comparison of quality criteria between the best experiment and the optimal condition indicate that TOPSIScan yield the maximum efficiency. Therefore, TOPSIS is the most suitable method in this study.

The results of the Taguchi–TOPSIS based MCDM of the process under lower vibration on the workpiece are analysed in this section. The largest increase in C_i under higher I and F could have resulted in increasing the optimal efficiency, as shown in Fig. 5a and d. Hence, the frequency associated with the specimen in EDM contributed on improving the machining efficiency. The change in T_{on} led to a change in the increase in the value of C_i (Fig. 5b). The influence of T_{off} on C_i conflicted with that of I and F on C_i (Fig. 5c). A higher T_{off} could lead to a significant reduction in the optimal efficiency. The significance of the factors on C_i is illustrated in Table 7. It was inferred that F has the strongest effect on performance measures in the vibration-assisted EDM process.

The 3D surface plots offer detailed knowledge about the interaction between the factors obtained using the Minitab software package. Figure 6 illustrates the interactions among process factors on C_i. The largest value of C_i corresponding to all interactionswas computed. The optimal effect is the larger corresponding to the interaction pairs I = 8A and T_{on} = 25μs in Fig. 6a, T_{off}= 5.5 μs and T_{on}=25μs in Fig. 6b, I = 8A and T_{off} = 5.5μs in Fig. 6c, F = 512 Hz and T_{on}=50μs in Fig. 6d, F = 512 Hz and T_{off} =5.5μs in Fig. 6e, and F = 512 Hz and I = 8A in Fig. 6f. Figure 7 shows the allotment of the C_i value to all interactions. The results show that the interaction combinations between F and the remaining parameters could make the distribution area of Ci > 0.5 be larger and the distribution area of Ci > 0.5 be the largest for the interaction pair between I and F. This shows that interaction of I and F can greatly affect the increase in C_i. This could strongly affect the machining efficiency. Hence, it was found that TOPSIS could predict the optimal process parameters with better accuracy. Table 8 shows the optimum quality indicators in the MCDM of EDM with lower vibration by the Taguchi-TOPSIS approach. It was found to beT_{on}=12

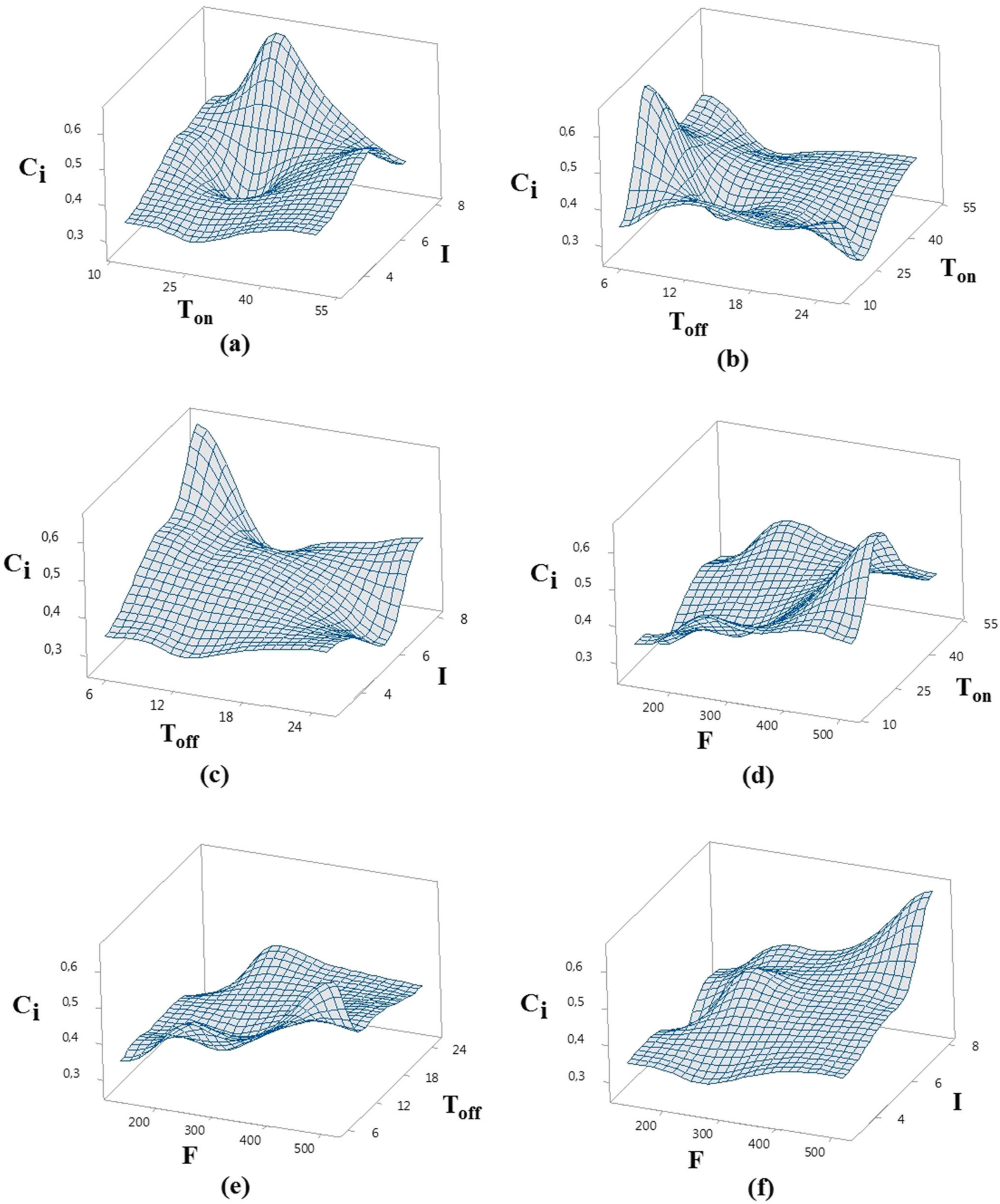


Fig. 6 Response surface of C_i vs. Interactive pairs between process parameters

μs, I = 8A, T_{off} =5.5μs, and F = 512 Hz. The optimal machining conditions were empirically verified and tabulated, as shown in Table 9. The larger deviation between calculation and experiment was 10.4%, which makes the method the most suitable in the present study.

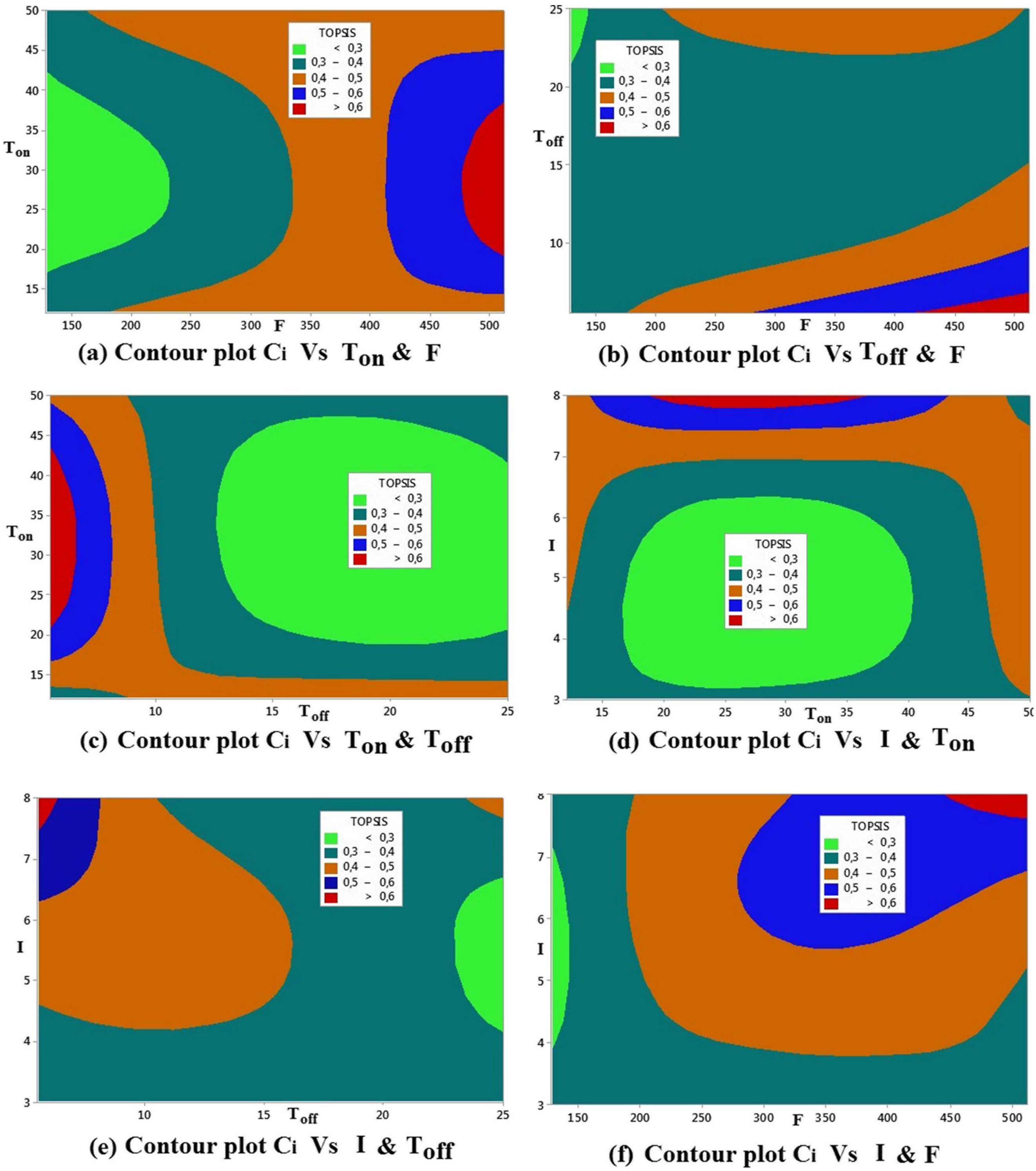


Fig. 7 Surface and contour plots for C_i of TOPSIS

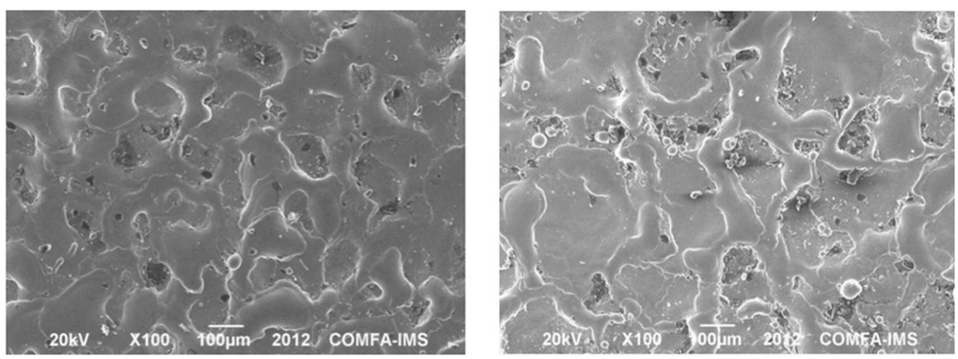
The quality of the surface under TOPSIS-based MCDM is shown in Fig. 8. The vibration could enhance the surface quality by reducing the crater size. Owing to the effect of lower vibration assigned to the workpiece in such a process, the number of sparks formed during a single pulse increased. As compared with traditional EDM, the elements on the machining surface using EDM under vibration were also significantly reduced, as shown in Fig. 9. Because the vibration facilitates the exclusion of the chip from the gap, the specimen and electrode were melted and evaporated. Adhesion to the machining surface was reduced. This could affect the

Table 8 Response Table for Means

Level	I	T_{on}	T_{off}	F
1	0.3540	0.4097	0.4930	0.3203
2	0.3947	0.4147	0.3697	0.4157
3	0.4843	0.4087	0.3703	0.4970
Delta	0.1303	0.0060	0.1233	0.1767
Rank	2	4	3	1

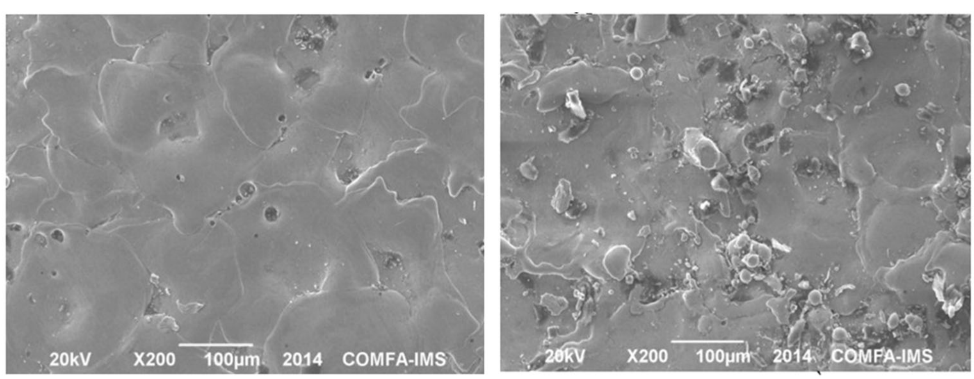
Table 9 Confirmation of experimental results

Quality criterias	Optimal process parameters	Optimal responses value		Difference (%)
		Cal.	Exp.	
MRR (mm^3 / min)	I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 512 Hz	9.87	9.74	-1.3
R_a (µm)		4.79	4.32	-9.8
HV (HV)		683	663.2	-2.9
WLT (µm)		17.42	15.61	-10.4



(a) under I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 512 Hz **(b) under I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 0 Hz**

Fig. 8 Craters on the machining surface



(a) under I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 512 Hz **(b) under I = 8A; T_{on} = 12 µs; T_{off} = 5.5 µs; F = 0 Hz**

Fig. 9 Particles on the machining surface

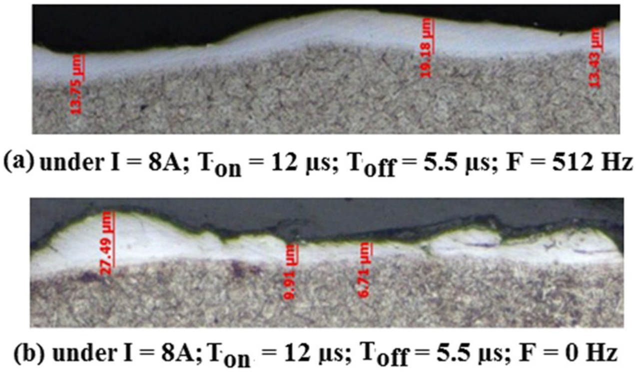


Fig. 10 Recast layer thickness on machined surface

machining mechanism. The WLT thickness on the machining surface in the machining process with vibration was better than in EDM without vibration, as illustrated in Fig. 10. Due to the higher even distribution of sparks under the influence of vibration, better surface quality could be obtained.

4 Conclusions

In the present study, various multi-attribute optimization approaches were implemented and compared. The influence of vibrations on the MRR, R_a, HV, and WLT was investigated. The efficacy of the optimization methods for performance measures was also investigated. The subsequent findings were found from the analysis.

- The integration of optimal vibration with the specimen has a positive effect on productivity and quality.
- The TOPSIS method provided better prediction accuracy in the present study.
- The frequency strongly influences on determining the quality measures based on the TOPSIS method.
- The optimal process parameters were found to be I = 4A, T_{on}=12 µs, T_{off} =5.5µs, and F = 512 Hz among the chosen factors and variables with an accuracy of 10.4%.
- The lower-frequency vibration associated with the workpiece in EDM contributes to a significant increase in surface quality.

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