Response Optimization of EDM process for AISI Tungsten Molybdenum High Speed (M2) Tool Steel Using Different Electrodes

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Abstract- **The present work aims to examine the machinability features of tungsten-molybdenum tool steel (M2 Steel) utilizing the electric discharge machining (EDM) process with copper and graphite electrodes. The experimentation model was confined in line to the Taguchi L_{27} orthogonal array. Peak current (I_P), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and voltage (v) were considered as process parameters. Signal-to-noise (S/N) ratios, main effect plots, and regression analysis have been utilized to assess the outcomes of the experimentation. Through the Taguchi's method, the optimal process parameters were confirmed concerning the output responses for material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR). The optimum levels of the factors for machining responses were determined by Taguchi's response graphs and analysis of variance (ANOVA) analysis. surface roughness, material removal rate, and electrode wear rate. The optimal levels for MRR were noticed as A3B2C1D3 for copper and A3B2C3D1 for the graphite electrode. The optimal levels were noticed to be A1B1C1D1 for surface roughness for both the electrodes. The optimal levels for EWR were noticed as A1B1C2D3 for copper and A1B3C1D1 for the graphite electrode. Results from the ANOVA consequences revealed that peak current (I_P) was noticed as the key influential process parameter followed by the pulse-on time (T_{ON}) on machinability. Results from the confirmatory experiments were closely in agreement with experimental results.**

Keywords – EDM, Copper, Graphite, ANOVA, Taguchi, Optimization

I. Introduction

Electric discharge machining (EDM) is a most versatile machining process for producing the intricate geometries and cavities that are not likely possible through another manufacturing process (traditional machining methods); extreme hard materials like High-Speed steels, Nickel alloys, Carbides, and other composites, etc. can be effortlessly processed. The material erosion in the EDM process is accomplished for removing the undesired elements in EDM occasion by the development of incessant sparking in the inter-electrode gap between the workpiece and tool-electrode submerged in the dielectric fluid. Owing to the melting and vaporization phenomenon the undesired materials in the form of debris particles are evacuated by the dielectric flushing and fresh dielectric fluid enters into the scene until the required shape attainment. Owing to the progression in the lifestyles of humans, it is necessary to improve the features of the prevalent materials or any alternates are so developed for new material applications. Machining is the only compatible with processing for these advanced materials [1]. In this sequence, Tungsten-molybdenum high-speed tool steel (M2 Steel) is a novel material that has extreme applications in tool and die-making, and other emerging areas for the automobile, defense, architectures, aerospace, and other bio-medical segments. In the present world, for competitiveness in the manufacturing scenario, there needs a fine balance among the quality and economy besides satisfying the customer needs. Higher precision and accuracy in the manufacture of typical profiles is the principal advantage of the EDM process. This process plays a key role in marine, defense, and aerospace sectors for the fabrication of higher stresses and temperature resistant components like fuel and engine systems, and other geared components. In the machining phenomenon, qualitative features always target a better surface finish with an increased material removal rate. Therefore, owing to this to contradictory requirements for the machining execution, it turns out to be a challenging task to attain the optimal settings. To solve this type of multifaceted matters, the engineering optimizations play a crucial role in the choice of optimal conditions for process parameters.

Extensive researches have been performed on the investigational studies on the modeling of thermal features and response optimizations of the EDM process to enhance its accuracy and precision. The machining performance and optimization for the process parameters of Al2O3–TiC Ceramic materials using EDM based on the Taguchi methodology and optimal parameter settings for processing the conductive-ceramics through this process were presented [2]. The process parameter optimization for the EDM process on ZrO2 ceramic material utilizing the Taguchi's response methodology. This study established a technically-feasible optimization process for the parametric levels for machining the non-conductive ceramic materials through the EDM process [3]. In later years the optimization process for EDM of 17-4-ph steel utilizing Taguchi's methodology is presented [4]. The machining responses EWR and MRR with L_{27} and reached the optimum parameter levels for pulse-on time, peak current, and gap-voltage conditions [4]. Optimization for SR, EWR, and MRR of SS 304 with L_9 OA and of Ti-6Al-4V alloy with Taguchi methodology and noticed the enhanced results in all machining responses for the different parametric settings [5]. A novel technique for deep-hole drilling through micro-EDM has been presented in the later years. A tube-electrode coated with the low electrical-conductive materials is utilized for the decrease of the detrimental discharges by controlling the sparks among the tool-flanks and work-piece. This research reported the decrease of tool-wear by the two folds with the 30 % improved aspect ratios with the coatings on tool-electrode [6]. The effects of the higher spindle speeds on the machining performance of the micro-hole drilling for EDM. They have reported that MRR and SR improvement with higher rotational speeds of tool-electrode, which resulted, a deep micro-holes with reduced tool-wear rate [7]. Improvement in MRR responses of 0.029 gm/min and EWR of 0.023 gm/min for EN-24 tool-steel utilizing Taguchi methodology and measured ANOVA for the machining responses were reported [8]. Optimization for the response like material erosion on Ni-Ti material with copper-tool as tool-electrode and attained the optimum MRR of 7.081 mm3/min were reported [9]. The effect of process parameters and their optimal settings for machining for MRR, SR, and EWR on M-D-N 300 material with the Taguchi technique was investigated and also reported that peak-current is the key influential process parameter in contrast to the pulse-on time for EWR and MRR, while pulse on-time showed the significant influence for the responses SR and RWR [10]. The machinability studies on the EDM of Al–SiC functionally graded metal matrix composite using the die-sinker method reported that the pulse-current (39.40%) influenced the maximum in minimizing the output responses. Besides, the surface-morphology is also analyzed on the materials to notice the formation of craters beyond the erosion mechanisms [11]. The influence of tool-electrode materials on the machining responses of µ-EDM has reported that for the higher discharges the MRR, taper-angle, EWR, and overcut are more noticed [12]. This research also reported that when the thermal-conductivity, melting point, and boiling points of the tool-electrode materials are more, the EWR is lower. These literature reviews justified the importance of the optimization and the selection of the process parameters and tool-materials for the EDM process.

The key objective of the present work is to investigate the influence of various process parameters of EDM utilizing the Taguchi design technique. To develop the response models for EDM of Tungsten-molybdenum high-speed steel (M2 Steel) utilizing the design of experiments L_{27} orthogonal-array (OA). It has been reported that peak current, pulse-on time, and gap-voltage have a significant influence on the surface roughness, EWR, and MRR. The results obtained are analyzed for the choice of optimum settings of EDM process parameters for the ensured machining phenomenon of M2 steel to attain the increased material erosion and the finer surfaces. Statistical analysis has been performed on the experimentation data attained. Analysis of variance (ANOVA) is performed to measure the influence of process parameters on the machining responses and signal-to-noise (S/N) ratios are calculated to specify the optimum combination and the process-factor levels. To develop a standard relationship among the process parameters and machining responses multi-regression models were developed. As a final point, confirmatory experiments were performed to validate the usefulness of this suggested technique.

II. EXPERIMENTAL DETAILS

2.1 Experimental Setup

The experimentation has been performed utilizing a "SPARKONIX-S-35 ZNC (die-sinker) EDM machine" manufactured in India. The machine is provided with all necessary adjustments for the mounting of the tool-electrode and workpiece. The tool-electrode guiding servo consists of a precise spindle-drive servo mechanism, as represented in Fig. 1.

Figure 1. Die-Sinker EDM Machine (Make: Sparkonix S-35)

2.2. Workpiece and electrodes

The workpiece utilized for this experimentation is Tungsten-molybdenum high-speed steel (M2 Steel) widely applicable in tool and die making processes. The work material selected for this machining is in the form of a block 50 mm * 50 mm * 12 mm. Experimentation has been performed utilizing a pure graphite electrode. The properties of the selected work and tool-electrode materials are listed in Table 1 and Table 2 respectively.

Table-1 Chemical Composition of M2 High-Speed Tool Steel

Elements	**C**	**Cr**	**W**	**Mo**	**V**	**Si**	**S**	**P**	**Mn**	**Fe**
Weight in %	**0.9**	**4.1**	**6.1**	**4.92**	**1.78**	**0.38**	**0.001**	**0.025**	**0.25**	**Balance**

Table-2 Properties of Workpiece and Tool-electrodes

Material	**Properties**		
	Density (g/cm^3)	**Melting Point (ºC)**	**Thermal Conductivity (W/m.k)**
M2 High-Speed Tool Steel	**8.138**	**4680**	**41.5**
Copper	**8.960**	**1084**	**401**
Graphite	**2.26**	**3600**	**98**

2.3 Experimental procedure

The tool-electrode was polished utilizing a fine grade emery paper, and the workpiece was aligned to a precise profile using a surface grinder, before experimentation. From the viewpoint of measuring the MRR and EWR, it is essential to measure the initial and final weights of the workpiece and tool-electrodes. This task is accomplished using the Preci-Tech Series 2009/0.1-mg accuracy digital weighing balance. The tool-electrode and workpiece were connected to according to the positive polarity in EDM machining.

III. DESIGN OF EXPERIMENTS

The design of experiments (DOE) is a methodology that is utilized to specify the relations among the several process parameters influencing the machining output responses for that process. DOE includes the design of experiments for the specified process, in that all pertinent parameters are so speckled methodically. Later analyzing the experimental outcomes, the optimum settings, and process parameters that key influential parameters, and that are recognized. Amongst the several techniques of DOE, the Taguchi methods are robust.

The process parameters that are chosen for the experiments are peak current (I_P), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and gap voltage (v). Besides, the output responses are MRR, EWR, SR, and ROC. The tool-electrodes were made separately for every trial. The surface of the electrode is polished gradually with 400–1000 grit sand-paper. The machining time for each experiment is calculated using the stopwatch. The conventional dielectric fluid is selected for performing the machinability studies. The surface roughness has been measured using the Mitutoyo SJ 210 roughness tester. The average roughness (Ra) value has been considered as the mean of the measured responses on different locations of the machined samples. The MAB 220T accuracy 0.0001 g was utilized for weighing electrodes before and after the experiments. MRR and ER are calculated using Eqn. (1) and Eqn. (2) respectively. The set-up for the present experimental work is represented in Figure 1.

$$MRR = \frac{Volume\ of\ the\ work\ material\ eroded}{Time} mm^3/min \quad (1)$$

$$EWR = \frac{W_b - W_a}{Time * Density} mm^3/min \quad (2)$$

Where $W_b = Weight\ of\ the\ electrode\ before\ machining$
$W_a = Weight\ of\ the\ electrode\ after\ machining$

3.1. Experimental Design and Optimization

The machinability studies performed with several statistical analysis techniques have been utilized to decide the optimum settings for the process parameters and to conclude their influence on the machining responses. One of such response optimization techniques of these are the Taguchi's method and ANOVA analysis [13-14], Experimentation data sets have developed utilizing the Taguchi's concept. Consequently, the influence of the process parameters on the machining responses is calculated easily. The optimal test conditions may be decided to utilize the Taguchi's methodology. The ANOVA technique is utilized to measure the influence of the process parameters on the machined responses. It is also very crucial in experimentation for the explanation of the attained results to decide any relation among the process parameters and the attained outcomes. A statistical tool like regression-based analyses is a powerful tool for analyzing the attained responses. Regression analysis assists in investigating the source–outcome relationships. Different features are utilized in the estimation of experimental outcomes attained with Taguchi's methodology. The signal-to-noise (S/N) ratios are concentrated on the variability and means of the factors. The signal (S) parameter corresponds to the realistic reference attained from the actual system, whereas the noise (N) value corresponds to the factor that was considered for the experimentation still influencing the attained results. The noise (N) causing sources is considered as the variability which results in the aroused deviations from the anticipated value. Process parameters and their levels were listed in Table 3. In the present work, graphite tool-electrode is utilized for EDM, for three different levels for peak current (I_P), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and gap voltage (v) conditions were considered as process control factors. The Taguchi L_{27} experimentation design was utilized with Minitab-18 software.

Table 3 Process Parameters and their Levels for Machining

Parameter	Process Parameters					
	Coded	Symbol	Units	Levels		
				Low	Medium	High
Peak Current	**A**	I_P	**A**	**10**	**20**	**30**
Pulse-on Time	**B**	T_{ON}	**µs**	**100**	**200**	**300**
Pulse-off Time	**C**	T_{OFF}	**µs**	**20**	**30**	**40**
Voltage	**D**	V	**V**	**15**	**25**	**35**

IV.RESULTS AND DISCUSSION

4.1. Analysis of experimental results

The machining responses MRR, EWR, and SR outcomes that are processed utilizing graphite tool-electrodes have listed Table 4. From Table 4, the highest MRR response (104.958 mm3/min) was attained during the run conditions trial number 24 (I_P=30A, T_{ON}=200µs, T_{OFF}=40µs, v=35 V). Figure 2 and Figure 3 represents the influence of peak current (I_P) and pulse-on time (T_{ON}) on the MRR. This graph represents that the increase in peak current (I_P) results in increased MRR outcomes with the graphite-tool electrode. From the graphs, it could be noticed that the MRR responses tend to increase with an increase in peak current (I_P) and pulse-on time (T_{ON}).

It is significantly visualized from Fig. 4 and Fig. 5 that all responses remained straight that reveals that attained responses are in closely in-line with the original experimental results. It has been witnessed clearly that EWR tends to increase continuously with peak current. This outcome is closely in the agreement with the past researches that higher peak current results in increased wear of the tool-electrode. As the pulse-on time (T_{ON}) increases from 100 to 300 µs, EWR increased initially to a threshold limit of 200 µs and then further tend to decrease till 3000 µs. This could be accounted to reason that carbon layer deposition on the tool-electrode surfaces at extended pulse durations, which in turn very rigid and also restricts the additional wear of the tool-electrode by forming the protective layer [15].

Results from Fig. 6 and Fig. 7 represents the influence of peak current (I_P) and pulse-on time (T_{ON}) on the SR. The graph represents that with the increase in peak current (I_P) occasioned higher SR outcome with graphite tool-electrodes. It is also noticed that gap voltage (v) and pulse-off time (T_{OFF}) have very limited influence on the SR. This could be occasioned for the reason that the increase in peak current (I_P) results in the higher impulsive forces that act on the workpiece [16]. This improves the development of deeper and larger size crater formations and in turn higher material erosion. Another reason could be the increase in peak current (I_P) occasion higher material erosion which in turn results in the formation of rougher surfaces on the workpiece.

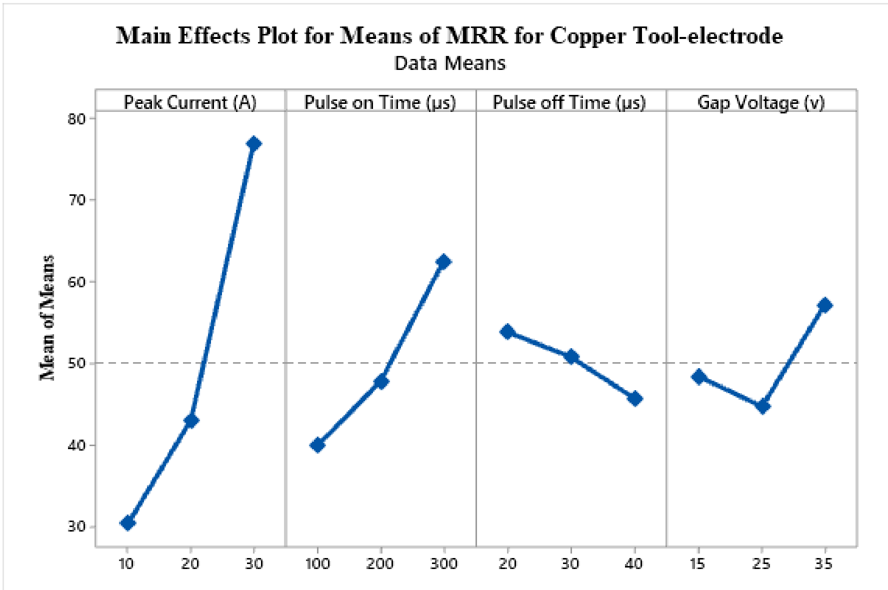

Figure 2. Main Effects Plot of MRR for Copper Tool-electrode

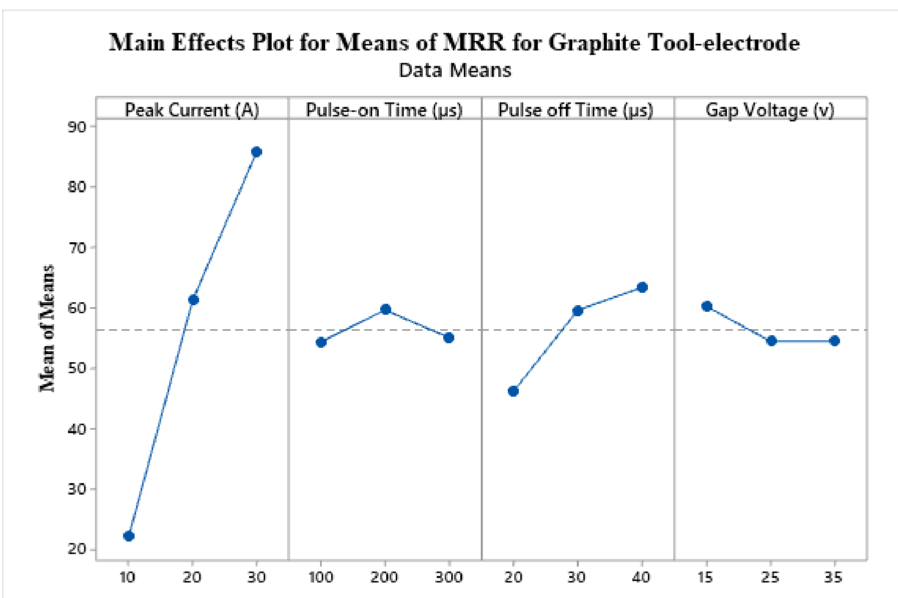

Figure 3. Main Effects Plot of MRR for Graphite Tool-electrode

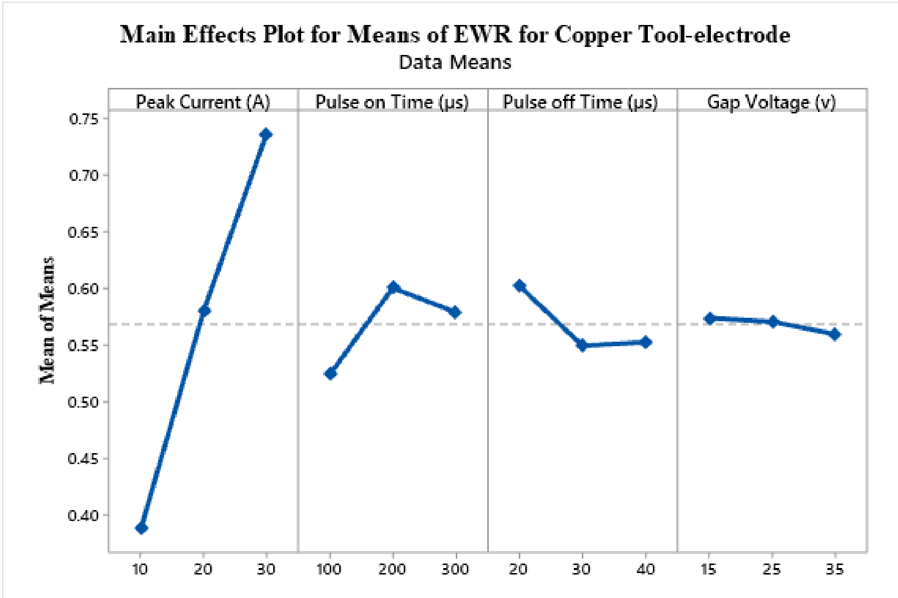

Figure 4. Main Effects Plot of EWR for Copper Tool-electrode

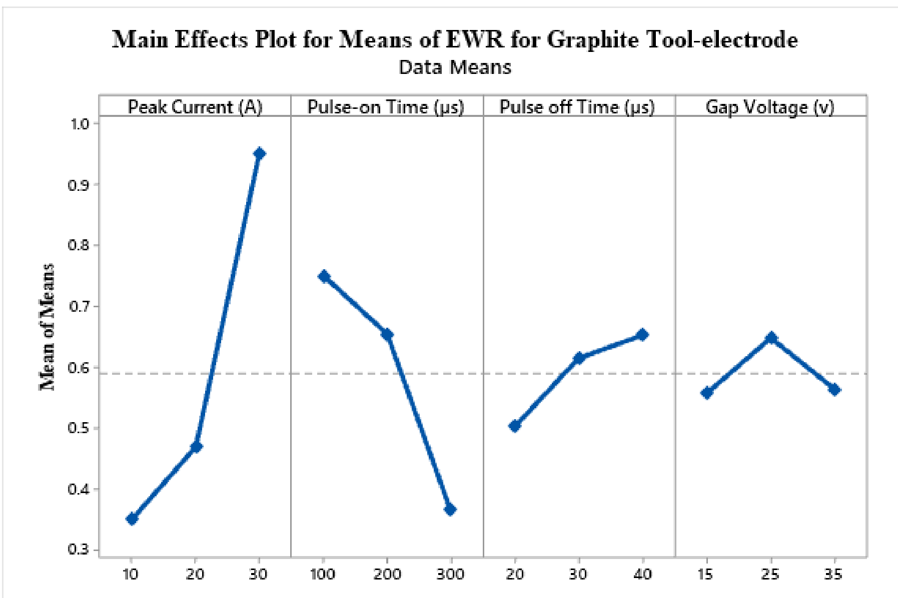

Figure 5. Main Effects Plot of EWR for Graphite Tool-electrode

Therefore, it can be determined that directly proportional trends of SR are witnessed with the rise in peak current (I_P). The gas bubbles severely influenced the SR owing to the quick quenching effects of the dielectric fluid and have been noticed on the machined surface. Figure 6 represents the influence of the peak current (I_P) and pulse-on time (T_{ON}) on MRR. The same consequences have been witnessed that with the increase peak current (I_P) resulted in an increase of the MRR for similar parametric conditions for both copper and graphite tool-electrodes [17]. This could be possibly occasioned for the increased melting and vaporization credentials of the work material surface per unit pulse duration. These consequences resulted in increased MRR instances. The least SR (11.157 µm) is noticed for the trial number 25 (I_P= 30 A, T_{ON}= 300µs, T_{OFF} = 20µs, v = 25 V). As the EDM is an erosion based process, the arc developed in between the tool-electrode and the work surface is stochastic and erratic. Consequently, the surface roughness could not be exactly estimated in advance. An increase in the peak current amplifies the intensified arcing conditions which are transferred to the work surfaces and severely occasions in deep crater formations with deprived surface formations. The dielectric fluid plays a crucial role in quenching and also removal of large debris particulates from the machining zone. These circumstances allowed increased MRR. It is also known that prolonged discharges implied to the work material surface result in the increase of melting and vaporization.

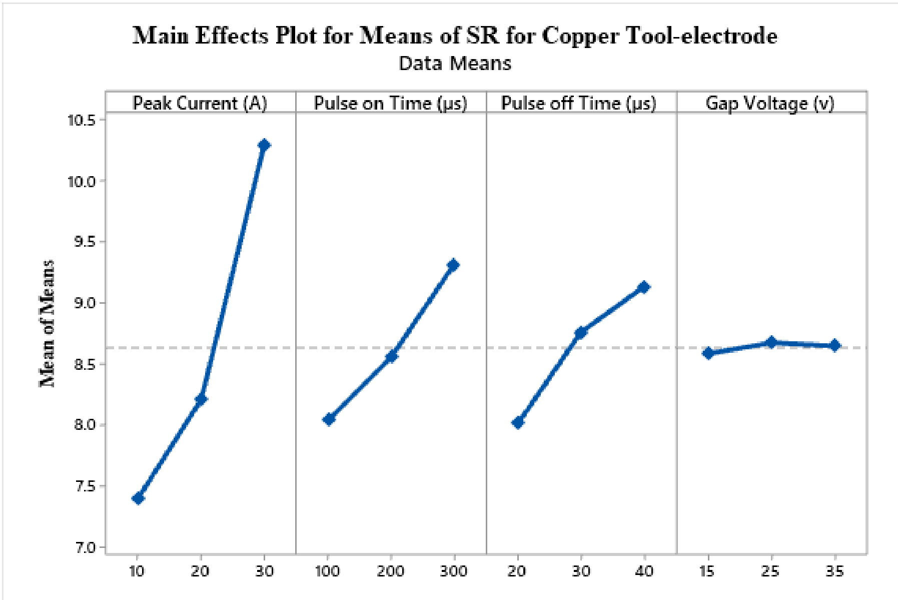

Figure 6. Main Effects Plot of EWR for Copper Tool-electrode

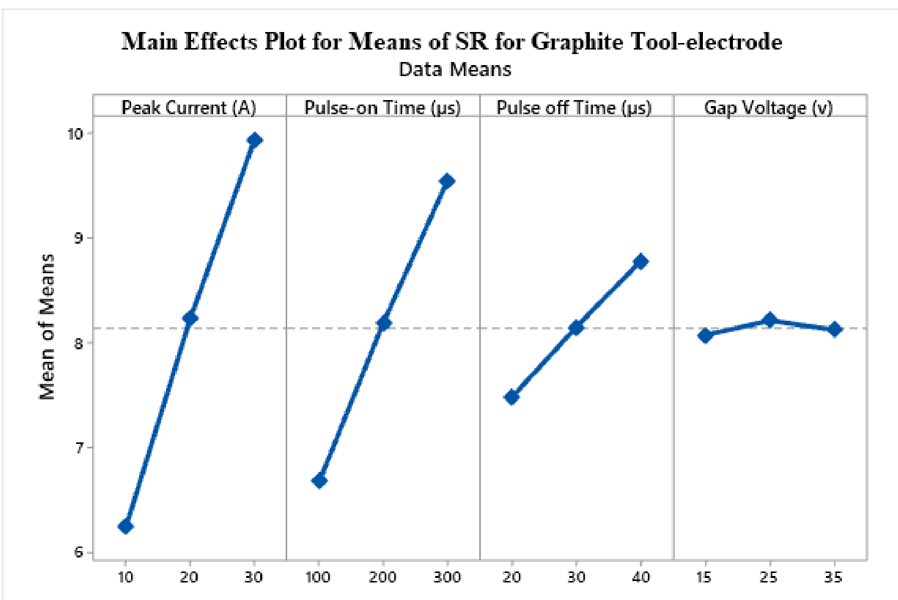

Figure 7. Main Effects Plot of EWR for Graphite Tool-electrode

4.2. S/N ratio analysis

In this area, the optimum levels for machining responses are estimated utilizing the Taguchi S-N ratios analysis. For the machining responses like MRR, the “larger-is-better” criterion, for EWR and SR “smaller-is-better” features was selected. The calculations are done based on the formulae listed in Eqn. (3) and Eqn. (4) respectively.

Smaller-is-Better characteristics, $$\eta = -10 \times \log \frac{1}{n} \sum_{i=1}^{n} y_i^2 \quad (3)$$

Larger-is-Better characteristics, $$\eta = -10 \times \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \quad (4)$$

Table-4 S-N Ratios for Material Removal Rate (MRR) for Different Tool-Electrodes

Factors	Copper Tool-electrode				Graphite Tool-electrode			
	I_P	T_{ON}	T_{OFF}	v	I_P	T_{ON}	T_{OFF}	V
1	29.28	31.08	33.56	32.6	26.64	33.44	31.87	34.39
2	32.33	32.88	33.41	32.12	35.64	34.05	34.06	33.39
3	37.55	35.2	32.19	34.44	38.55	33.33	34.89	33.04
Delta	8.27	4.12	1.38	2.32	11.92	0.72	3.02	1.34
Rank	1	2	4	3	1	4	2	3

Table 5. S-N Ratios for Electrode Wear Rate (EWR) For Different Tool-Electrodes

Factors	Copper Tool-electrode				Graphite Tool-electrode			
	I_P	T_{ON}	T_{OFF}	v	I_P	T_{ON}	T_{OFF}	V
1	8.273	5.861	4.743	5.321	13.518	3.1794	8.3755	9.7224
2	4.77	4.736	5.486	5.107	8.5578	5.0717	8.6924	4.2691
3	2.727	5.174	5.541	5.342	0.6942	14.5189	5.7021	8.7786
Delta	5.545	1.125	0.798	0.236	12.8239	11.3395	2.9903	5.4533
Rank	1	2	3	4	1	2	4	3

Table-6 S-N Ratios for Surface Roughness (SR) for Different Tool-Electrodes

Factors	Copper Tool-electrode				Graphite Tool-electrode			
	I_P	T_{ON}	T_{OFF}	v	I_P	T_{ON}	T_{OFF}	V
1	-15.8	-16.3	-17.16	-17.94	-17.36	-18	-17.96	-18.57
2	-18.09	-18	-17.94	-17.9	-18.21	-18.52	-18.72	-18.63
3	-19.88	-19.46	-18.67	-17.92	-20.23	-19.28	-19.11	-18.6
Delta	4.08	3.16	1.51	0.04	2.86	1.28	1.15	0.07
Rank	1	2	3	4	1	2	3	4

where η denotes the S-N ratio, 'y_i' denotes the response values and the n denotes the number of iterations. The corresponding S-N ratios for MRR, EWR, and SR for the different electrodes are listed in Table 4, Table 5, and Table 6 respectively.

4.3. Analysis of variance

Analysis of variance (ANOVA) is utilized to measure the parameter's influence on the output responses for the selected components. ANOVA is majorly confined for all machining responses like MRR, EWR, and SR. The attained results are listed in Table 7,8 and 9 correspondingly.

Table-7 ANOVA for Material Removal Rate (MRR) for Different Tool-Electrodes

		Carbon Tool-electrode			Graphite Tool-electrode		
Sources	DoF	SS	MS	F-test	SS	MS	F-test
I_P	2	10458.4000	5229.2000	153.5400	18628.5000	9314.2600	175.7800
T_{on}	2	2358.3000	1179.1700	34.6200	145.7000	72.8300	1.3700
T_{off}	2	303.6000	151.7900	4.4600	1483.7000	741.8700	14.0000
v	2	743.1000	371.5400	10.9100	197.3000	98.6700	1.8600
Error	16	613.0000	34.0600		953.8000	52.9900	
Total	26	14476.4000			21409.0000		

Table-8 ANOVA for Electrode Wear Rate (EWR) for Different Tool-electrodes

		Carbon Tool-electrode			Graphite Tool-electrode		
Sources	DoF	SS	MS	F-test	SS	MS	F-test
I_P	2	0.5478	0.2739	59.0800	1.8222	0.9111	30.0000
T_{on}	2	0.0278	0.0139	3.0000	0.7179	0.3590	11.8200
T_{off}	2	0.0158	0.0079	1.7100	0.1090	0.0545	1.8000
V	2	0.0010	0.0005	0.1100	0.0457	0.0229	0.7500
Error	16	0.0835	0.0046		0.5466	0.0304	
Total	26	0.6759			3.2415		

In ANOVA analysis, 95% confidence levels are measured, which reflects as the '$p \geq 0.05$' then that parameter is decided as in-significant. R^2 is accountable in determining the estimated variance levels for the models, while R^2-adj is accountable for the decision of several predictions for the variance model developed [18]. The corresponding ANOVA for MRR, EWR, and SR for the different electrodes are listed in Table 7, Table 8, and Table 9 respectively.

Table-9 ANOVA for Surface Roughness (SR) for Different Tool-electrodes

		Carbon Tool-electrode			Graphite Tool-electrode		
Sources	**DoF**	**SS**	**MS**	**F-test**	**SS**	**MS**	**F-test**
I_P	2	40.2408	20.1204	83.5100	61.5880	30.7941	80.1000
T_{on}	2	7.3408	3.6704	15.2300	36.7940	18.3972	47.8500
T_{off}	2	5.8664	2.9332	12.1700	7.5910	3.7957	9.8700
V	2	0.0371	0.0186	0.0800	0.0870	0.0436	0.1100
Error	16	4.3367	0.2409		6.9200	0.3844	
Total	26	57.8219			112.9810		

4.4. Confirmatory Experiments

Confirmatory experiments ensure the stability for the improvements in the process improvements that would result from optimum-parameter settings. The confirmatory experiments for the present investigation are listed n Table 10 and Table 11 respectively.

Table-10 Optimal Set of Process Parameters for Copper Tool-electrode

S.No	Performance Measures	Optimal Process Parameter Combination				Response Characteristic Values		% Improvement with Optimization
		I_P	T_{ON}	T_{OFF}	v	OA	Confirmation Experiment	
1	MRR (mm^3/min)	Level 3	Level 3	Level 1	Level 3	100.874	109.690	8.61
2	EWR (mm^3/min)	Level 1	Level 1	Level 2	Level 3	0.3283	0.3254	2.57
3	SR (μm)	Level 1	Level 1	Level1	Level 1	6.566	6.331	3.54

Table-11 Optimal Set of Process Parameters for Graphite Tool-electrode

S.No	Performance Measures	Optimal Process Parameter Combination				Response Characteristic Values		% Improvement with Optimization
		I_P	T_{ON}	T_{OFF}	V	OA	Confirmation Experiment	
1	MRR (mm^3/min)	Level 3	Level 2	Level 3	Level 1	104.958	109.311	4.14
2	EWR (mm^3/min)	Level 1	Level 3	Level 1	Level 1	0.00692	0.0066	3.65
3	SR (μm)	Level 1	Level 1	Level1	Level 1	5.097	4.951	1.42

V. CONCLUSIONS

In the present work, the effect of the copper and graphite tool-electrodes has been explored for EDM of tungsten-molybdenum high-speed steel M2 High-Speed Steel (M2 steel). The consequent and significant conclusions were reached after this investigation:

- The highest MRR responses are attained at the maximum values of peak current (I_P) and pulse-on time (T_{ON}) settings. Moreover, high MRR responses are witnessed with graphite tool-electrode in contrast to that of the copper tool-electrode.
- Peak current (I_P) and pulse-on-time (T_{ON}) are witnessed as the crucial factors that influence EWR, whereas pulse-off time (T_{OFF}) and voltage factors have limited influence on EWR. It is witnessed that more EWR with graphite electrode in contrast to that of copper tool-electrode at (I_P= 20 A and T_{ON} = 200 μs), this could be accounted for the increased material erosion.
- Under similar experimental conditions, lower SR values were witnessed with the graphite tool-electrode in contrast to that of the copper tool-electrode. The finer surfaces with the graphite electrode could be accounted for the higher melting point of graphite as compared to that of the copper tool.
- Results from the Taguchi's response optimization, the optimal parameter settings for SR (A1B1C1D1 for copper and graphite). The best surface roughness has been witnessed with the graphite electrode (SR= 5.097 μm at Trial number 1)

- The calculated responses for the investigated results and the predicted results were in close agreement, thus determining the effectiveness of the response optimization.

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