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ORIGINAL ARTICLE

Influence of parameters and optimization of EDM performance measures on MDN 300 steel using Taguchi method

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Abstract Maraging steel (MDN 300) exhibits high levels of strength and hardness. Optimization of performance measures is essential for effective machining. In this paper, Taguchi method, used to determine the influence of process parameters and optimization of electrical discharge machining (EDM) performance measures on MDN 300 steel, has been discussed. The process performance criteria such as material removal rate (MRR), tool wear rate (TWR), relative wear ratio (RWR), and surface roughness (SR) were evaluated. Discharge current, pulse on time, and pulse off time have been considered the main factors affecting EDM performance. The results of the present work reveal that the optimal level of the factors for SR and TWR are same but differs from the optimum levels of the factors for MRR and RWR. Further, discharge current, pulse on time, and pulse off time have been found to play a significant role in EDM operations. Detailed analysis of structural features of machined surface was done by using scanning electron microscope (SEM) to understand the influence of parameters. SEM of electrical discharge machining surface indicates that at higher discharge current and longer pulse on duration give rougher surface with more craters, globules of debris, pockmarks or chimneys, and microcracks than that of lower discharge current and lower pulse on duration.

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Keywords Electrical discharge machining (EDM) · Maraging steel · Discharge current · Pulse on time · Pulse off time · Orthogonal array

1 Introduction

Electrical discharge machining (EDM) is an important manufacturing process for machining hard metals and alloys [1]. This process is widely used for producing dies, molds, and finishing parts for aerospace, automotive, and surgical components [2]. The process is capable of getting required dimensional accuracy and surface finish by controlling the process parameters [3]. EDM performance is generally evaluated on the basis of material removal rate (MRR), tool wear rate (TWR), relative wear ratio (RWR), and surface roughness (SR) [2]. The important EDM machining parameters affecting to the performance measures of the process are discharge current, pulse on time, pulse off time, arc gap, and duty cycle [4].

A considerable amount of work has been reported by the researchers on the measurement of EDM performance on the basis of MRR, TWR, RWR, and SR for various types of steels. Rao et al. [5] studied the influence of process parameters on EDM of MDN 250 steel. They have considered discharge current, pulse on time, and duty factor as performance measures whereas process parameters are MRR and SR. However, in their study, parametric optimization was not done. TWR and RWR ratios were not considered. Furthermore, they extended their studies and developed a hybrid model for SR is to predict the behavior of the MDN 250 steel [6].

MDN 300 steel possesses an extreme resistance to crack propagation, even in the most extreme environments. It is used in applications where high fracture toughness is required or where dimensional changes have to remain at a minimal level. It is specially used in effective in the design of power shafts and low-

Table 1 Chemical composition of MDN 300 steel

Alloying element	Ni (%)	Co (%)	Mo (%)	Ti (%)	Fe (%)	C (%)	Al (%)
Amount	17–19	12	3–5	0.2–1.6	65–68	0.01	0.10

temperature cooling systems, rocket motor casings, and the landing gear for certain planes [7]. The properties and applications of both MDN 250 steel and MDN 300 steel are different. MDN 300 steel has less thermal conductivity than MDN 250 steel; hence, MRR is different. In addition to this, the chemical composition shows cobalt is not present in case of MDN 250 steel which affects the hardness at elevated temperatures. The melting point of MDN 300 steel is 1,427–1,454 °C whereas the melting point of MDN 250 is 1,435–1,505 °C. However, it has not been found that there is no available result of the EDM process of this material. Therefore, it is imperative to develop a suitable technology guideline for optimum EDM of MDN 300 steel.

In EDM, for optimum machining performance measures, it is an important task to select proper combination of machining parameters [8]. Generally, the machining parameters are selected on the basis of operator's experience or data provided by the EDM manufactures. When such information is used during EDM, the machining performance is not consistent. Data provided by the manufacturers regarding the parameter settings is useful only for most commonly used steels. Such data is not available for special materials like Maraging steels, ceramics, and composites. For these materials, experimental optimization of performance measures is essential. Optimization of EDM process parameters becomes difficult due to more number of machining variables. Slight changes in a single parameter significantly affect the process. Thus, it is essential to understand the influence of various factors on EDM process. Analytical and statistical methods are used to select best combination of process parameters for an optimum machining performance.

Table 2 Properties of MDN 300 steel

Property	Quantity
Density	8.1 g/cm^3
Specific heat, mean for 0–100° C	813 J/kg° K
Melting point	1,427–1,454° C
Thermal conductivity	25.8 W/m K
Yield tensile strength	758 MPa
Electrical resistivity	$0.174\times10^{-4}\Omega$ cm
Hardness	34 BHN

Table 3 Working range of the process parameters and their levels

Symbol	EDM parameter	Unit	Level 1	Level 2	Level 3
A	Discharge current	A	10	15	20
B	Pulse on time	μs	25	45	65
C	Pulse off time	μs	24	36	48

The present work describes the optimization of the EDM performance measures using Taguchi method. In this method, it is required to consider all aspects of the design that affect the deviation of functional characteristics of the product from target values. It is also essential to consider methods to reduce undesirable and uncontrollable factors that can cause functional deviations [9]. It is possible to evaluate the effects of individual parameter independent of other parameters and interactions on the indentified quality characteristics by using this method [10–12]. Taguchi method is one of the popular methods used for optimization as it requires minimum experimental cost and decreases the effect of the source of variation effectively [13]. TWR is an important performance measure as it affects to the geometrical and dimensional accuracy of the machined surface. It is an independent performance measure and depends on process parameters. Also, it gives an amount of tool material eroded from the tool in a given time. RWR is an important performance measure as it gives the amount of tool material eroded as compared to MRR. So, RWR depends on MRR and TWR. Both the factors will minimize the objective function; hence, we considered both MRR and RWR in the present study.

2 Scheme of investigation

In order to maximize the desirable performance measures and minimize undesirable performance measures, the investigation was done in the following sequence:

Table 4 Experimental layout using an L_9 (3^4) OA

Sr. no.	EDM parameter		
	A Discharge current	B Pulse on time	C Pulse off time
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

- Selection of workpiece material and electrode material.
- Identify the important EDM process parameters.
- Determine the working range of the identified process parameters.
- Select the orthogonal array (OA; design of matrix).
- Conduct the experiments as per the selected OA.
- Record the performance measures (i.e., MRR, TWR, RWR, and SR).
- Find the optimum condition for performance measures and indentify the significant factors.
- Conduct the confirmation test.

2.1 Selection of the workpiece material and electrode material

The workpiece material employed in this study was MDN 300 steel. Copper was selected as an electrode material as it is commonly used because of its high thermal conductivity and electrical conductivity. The chemical composition and properties of MDN 300 steel are shown in Tables 1 and 2, respectively.

2.2 Identify the important EDM process parameters

On the basis of the literature [14] and previous work done [15, 16], it was concluded that the most important EDM process parameters which has greater influence on the MRR, TWR, RWR, and SR are discharge current, pulse on time, and pulse off time.

2.3 Determination of the working range of the process parameters

A large number of trials were conducted by varying one of the process parameters and keeping the other parameters constant. The working range of discharge current, pulse on time, and pulse off time was explored by inspecting the cavity produced in the workpiece by the electrode. The working range of the process parameters selected under the present study is indicated in Table 3.

2.4 Selection of OA

In this study, the number of process parameters considered were three and the level of each parameter was 3. The degrees of freedom of all three parameters were 2 (i.e., number of levels 1) and the total degrees of freedom of all the factors is 6 (i.e., $3\times2=6$). The selected orthogonal arrays (OA) degrees of freedom (DOF) (i.e., number of experiments, $1=9-1=8$) must be greater than the total DOF of all the factors (6). Hence, L_9 (3^4) OA is considered for the present study. Based on the preliminary experimentation, there is no interaction between the selected process

Table 5 Performance measures of EDM

Sr. no	MRR (mm³/min)				TWR (mm³/min)				RWR				SR (μm)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
1	15.41	16.11	15.77	15.76	3.86	4.65	4.36	4.29	25.24	29.35	27.41	27.33	5.69	5.58	5.59	5.62
2	24.98	26.86	25.86	25.92	4.79	5.65	5.24	5.22	19.19	21.5	19.78	20.15	6.69	6.51	6.63	6.61
3	29.49	30.57	30	30.02	3.47	4.57	4.05	4.03	11.8	14.93	13.39	13.37	7.58	7.84	7.73	7.71
4	28.2	29.12	28.63	28.65	7.32	8.61	7.98	7.97	25.96	29.58	27.74	27.76	5.59	7.35	6.51	6.48
5	39.62	40.11	39.88	39.87	8.39	9.06	8.74	8.73	21.18	22.58	21.9	21.88	7.5	6.4	7.12	7
6	30.06	29.95	29.96	29.99	6.9	7.4	7.12	7.14	22.96	24.74	23.79	23.83	7.54	7.05	7.36	7.32
7	29.24	31.92	30.57	30.57	8.47	10.5	9.51	9.48	28.98	32.78	30.94	30.9	5.78	6.09	5.89	5.92
8	41.19	41.4	41.35	41.31	10.25	10.7	10.47	10.46	24.89	25.74	25.36	25.33	6.47	7.39	7.03	6.96
9	49.85	52.29	52.02	51.38	13.68	12.3	12.99	13	26.25	24.55	25.34	25.38	7.9	8.37	8.18	8.15

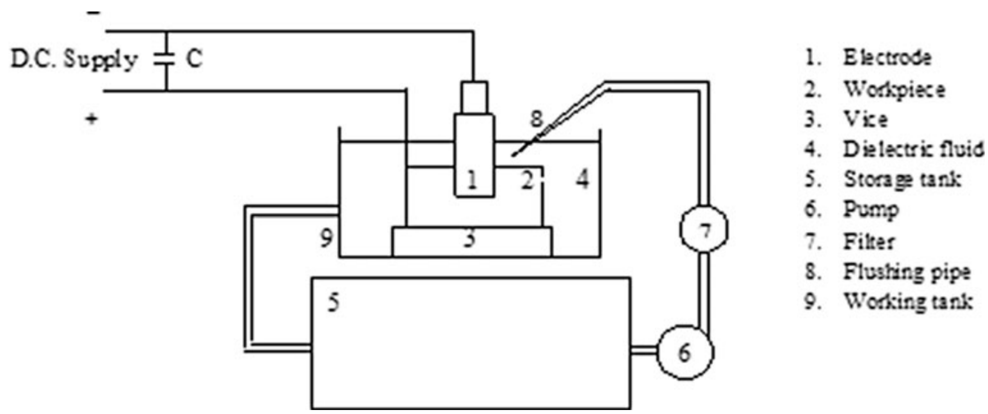

Fig. 1 Schematic diagram of die sinking EDM machine

parameters. Hence interaction is not considered for the present study. Three trails of each experiment were conducted to average of these values so that minimize the pure experimental error. The selected OA is presented in Table 4.

2.5 Conduct the experiments as per the selected OA

The workpiece material of 60 mm in diameter and 8 mm thick and the electrode of 12 mm diameter were used. The experiments were conducted as per the layout shown in Table 5. A Formatics EDM 50 die sinking machine with Electronica PRS-20 controller was employed for conducting the EDM experiments. Each experiment was conducted for a duration of 3 min. Prior to machining, the work pieces and electrode were cleaned and polished. The workpiece was firmly clamped in the vice and immersed in the electrol EDM oil. The positive polarity was used during the experiments. The schematic diagram of die sinking EDM machine is shown in Fig. 1.

2.6 Record the performance measures (i.e., MRR, TWR, RWR, and SR)

The machining performance measures were evaluated by MRR, TWR, RWR, and SR. The MRR is the workpiece weight loss (WWL) under a period of machining time in minutes, i.e.,

$$\mathrm{MRR}\left(\mathrm{mm}^3/\mathrm{min}\right) = \frac{\mathrm{WWL}\ (\mathrm{g}) \times 1,000}{\rho(\mathrm{g/cm}^3\ ) \times \mathrm{machining\ time(min)}}$$

ρ=density of workpiece material

The TWR is the tool weight loss (TWL) under a period of machining time in minutes, i.e.,

$$\mathrm{TWR}\left(\mathrm{mm}^3/\mathrm{min}\right) = \frac{\mathrm{TWL}\ (\mathrm{g}) \times 1,000}{\rho(\mathrm{g/cm}^3\ ) \times \mathrm{machining\ time(min)}}$$

ρ=Density of tool material

The RWR is defined as the ratio of the TWR to the MRR from the workpiece and is usually expressed as a percent.

$$\mathrm{RWR}\ (\%) = \frac{\mathrm{TWR}}{\mathrm{MRR}} \times 100$$

The SR is referred to the roughness or smoothness of a given surface. In this study, it was measured in terms of roughness average (R_a), which is an arithmetic average of peaks and valleys of a workpiece surface measured from the centerline of evaluation length. It was measured by Zeiss (Make:Surcom 130A) surface roughness tester. The machining performance measures, i.e., MRR, TWR, RWR, and SR were evaluated for all the conditions and presented in Table 5.

Table 6 Average experimental results of MRR, TWR, RWR, and SR and their corresponding S/N ratios

Sr. no.	MRR (mm^3/min)	S/N ratio (dB)	TWR (mm^3/min)	S/N ratio (dB)	RWR	S/N ratio (dB)	SR (μm)	S/N ratio (dB)
1	15.76	23.95	4.29	−12.64	27.33	−28.73	5.62	−14.99
2	25.92	28.27	5.22	−14.35	20.15	−26.08	6.6	−16.39
3	30.02	29.54	4.03	−12.1	13.37	−22.52	7.71	−17.74
4	28.65	29.14	7.97	−18.2	27.76	−28.87	6.48	−16.23
5	39.87	32.01	8.73	−18.82	21.88	−26.8	7	−16.9
6	29.99	29.53	7.14	−17.07	23.83	−27.54	7.32	−17.29
7	30.57	29.7	9.48	−19.53	30.9	−29.8	5.92	−15.44
8	41.31	32.32	10.46	−20.39	25.33	−28.07	6.96	−16.85
9	51.38	34.21	13	−22.28	25.38	28.09	8.15	−18.22

Table 7 S/N response table for MRR

Symbol	EDM parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max-min
A	Discharge current	23.9	32.84	41.09	17.19
B	Pulse on time	24.99	35.7	37.13	12.14
C	Pulse off time	29.02	35.32	33.49	6.3

The total mean S/N ratio=29.85

Table 8 S/N response table for TWR

Symbol	EDM parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max-min
A	Discharge current	−13.4	−17.97	−20.97	7.7
B	Pulse on time	−16.74	−17.85	−18.22	1.12
C	Pulse off time	−16.7	−18.22	−16.82	1.52

The total mean S/N ratio=−17.26

2.7 Find the optimum condition for performance measures and identify the significant factors

In Taguchi method, the effects of machining parameters on performance measures are evaluated under optimal condition. It is used to determine appropriate combination of machining parameters to maximize MRR and minimize TWR, RWR, and SR. The experimental results of MRR, TWR, RWR, and SR were further transformed into a signal-to-noise ratio (S/N) ratio. The characteristic that higher value represents better machining performance, such as MRR, is called "higher the better". The characteristics that lower the value represents better machining performance, such as TWR, RWR, and SR, is called "lower the better." Therefore, "higher the better" for the MRR, "lower the better" for TWR, RWR, and SR were selected for obtaining machining performance. Taguchi method uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio η is defined as

$$\eta = -10\log(\mathrm{MSD}) \qquad (1)$$

where MSD is the mean square deviation for the output characteristic.

To obtain optimal EDM performance, higher-the-better quality characteristic for material removal rate from workpiece must be taken. The MSD for higher-the-better quality characteristic can be expressed as:

$$\mathrm{MSD} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{\mathrm{MRR}_i^2} \qquad (2)$$

Where m is the number of tests and MRR_i is the value of MRR and ith test.

On the other hand, lower-the-better quality characteristics for TWR, RWR, and SR should be taken for obtaining optimal EDM performance. The MSD for lower the better quality characteristic can be expressed as:

$$\mathrm{MSD} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{TWR}_i^2 \qquad (3)$$

Where TWR_i^2 is the value of TWR for the ith test

$$\mathrm{MSD} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{RWR}_i^2 \qquad (4)$$

Where RWR_i^2 is the value of RWR for the ith test

$$\mathrm{MSD} = \frac{1}{m}\sum_{i=1}^{m}\mathrm{SR}_i^2 \qquad (5)$$

Where SR_i^2 is the value of SR for the ith test.

The average experimental results of MRR, TWR, RWR, and SR and their corresponding S/N ratios using Eqs. (1) to (5) are presented in Table 6.

After calculation of S/N ratio, the effect of each machining parameter at different levels can be separated. The mean S/N ratio for each machining parameter at each level was calculated by averaging the S/N ratios for the experiments at the same level for that particular parameter. Table 7 shows S/N response table for MRR and Fig. 2 shows the S/N response graph for MRR.

For performance measures like TWR, RWR, and SR, greater S/N ratios were considered as they result in smaller variance of the output about the targeted value. The experimental results for TWR and the S/N response graph for TWR are shown in Table 8 and Fig. 3, respectively. Table 9

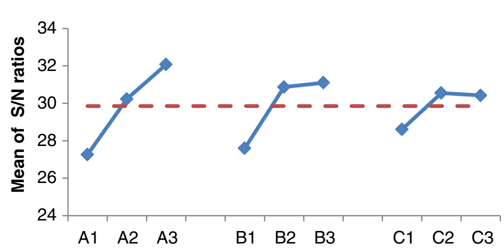

Fig. 2 S/N graph for MRR

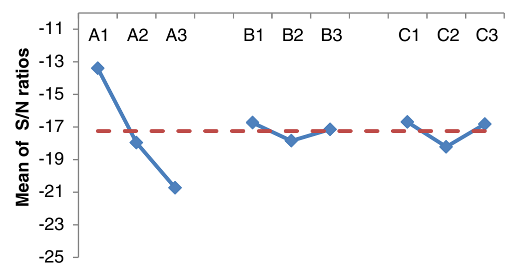

Fig. 3 S/N graph for TWR

Table 9 S/N response table for RWR

Symbol	EDM parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max–min
A	Discharge current	−25.78	−27.74	−28.65	2.87
B	Pulse on time	−29.13	−26.99	−26.05	3.08
C	Pulse off time	−28.12	−27.68	−26.37	1.74

The total mean S/N ratio=−27.22

Table 10 S/N response table for SR

Symbol	EDM parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max–min
A	Discharge current	−16.38	−16.81	−16.84	0.47
B	Pulse on time	−15.56	−16.72	−17.75	2.19
C	Pulse off time	−16.38	−16.95	−16.7	0.57

The total mean S/N ratio=−16.71

presents S/N response table for RWR and Fig. 4 shows the S/N response graph for RWR. Table 10 indicates S/N response table for SR and Fig. 5 shows the S/N response graph for SR.

The optimization of process parameters using Taguchi method [17] permits evaluation of the effects of individual parameters independent of the other parameters. The analysis of variance (ANOVA) is used to determine which design parameters significantly affect the performance measures [16]. In ANOVA, first total sum of squared deviations SS_T from total mean S/N ratio η_m can be calculated as

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \tag{6}$$

Where n is the number of experiments in the orthogonal array and η_i is mean S/N ratio for ith experiment.

ANOVA was applied to find out the significance of main factors and the F test was used to determine the process parameter significantly effect on the responses (MRR, TWR, RWR, and SR). Usually, the change of the EDM process parameter has significant effect on the response when F ratio is large. Table 11 shows the results of ANOVA for MRR. Table 12 presents the results of ANOVA for TWR. Table 13 shows the results of ANOVA for RWR. Table 14 shows the results of ANOVA for SR.

ANOVA also provides an indication of which process parameter combination is predicted and the optimum results. These optimum results are presented in Table 15.

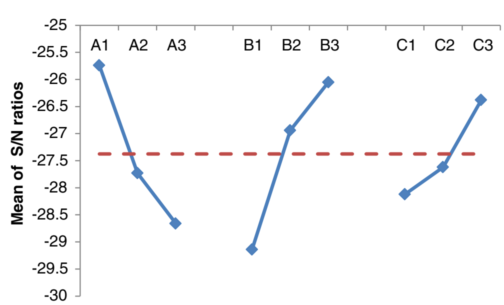

Fig. 4 S/N graph for RWR

2.8 Conduct the confirmation test

Optimum levels of design parameters were used for prediction and confirmation of the performance measures improvement. The estimated S/N ratio, $\hat{\eta}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o} (\hat{\eta}_i - \eta_m) \tag{7}$$

Where η_m is the total mean S/N ratio, $\hat{\eta}_i$ is the mean S/N ratio at the optimal level, and o is the number of main design parameters that affect the quality characteristic.

For validations of the optimum results, experiments were conducted as per the optimum conditions and machining performance measures were evaluated and the results are presented in Table 16. It is observed that, experimental values are closer to the optimum values.

3 Discussion

3.1 Effect of parameters on EDM performance measures

Based on the S/N ratio and ANOVA analysis of the result, various conclusions are drawn. As shown in Table 7 and Fig. 2, factors at level A_3 (discharge current, 20 A), B_3 (pulse on time, 65 µs), and C_2 (pulse off time, 36 µs) gives maximum MRR. Factor C is having least significant effect on improving MRR. The contribution order of machining parameters for MRR is discharge current, then pulse on time, and then pulse off time as shown in Table 11. The

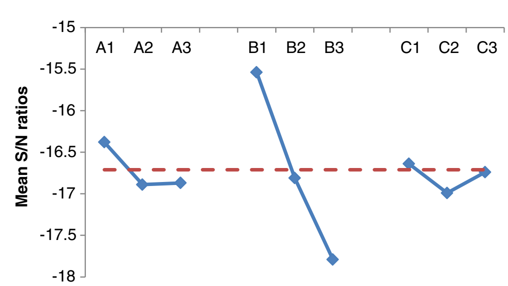

Fig. 5 S/N graph for SR

Table 11 Results of the ANOVA for MRR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	*F* ratio	Contribution (%)	*P* value
A	Discharge current	2	35.53	17.77	3.3	52.4	0.011
B	Pulse on time	2	23	11.5	1.54	33.92	0.029
C	Pulse off time	2	7.1	3.5	0.35	10.47	0.072
Error		2	2.17			3.2	
Total		8	67.8			100	

heat energy supplied to remove the workpiece material is controlled by the discharge current. Hence, the contribution and significance of discharge current is largest. The pulse on time controls the duration of time for which the current is allowed to flow per cycle. The material removed from the workpiece is directly proportional to the amount of energy supplied during this period. Thus, it is the second factor as far as contribution and significance is concern. During the pulse off time, no material is removed from the workpiece as there is no discharge current supplied. This results in lowest significant effect and lowest contribution for MRR.

From Table 8 and Fig. 3, it is recommended to use the factors at level A_1 (discharge current, 10 A), B_1 (pulse on time, 25 μs), and C_1 (pulse off time, 24 μs) to minimize TWR. Table 12 shows that the contribution of factors *B* and *C* is very less to minimize TWR. The amount of heat energy depending on the discharge current is also utilized to remove material from the tool. This results in largest significance and contribution of discharge current towards TWR. The electrode is exposed to less heat than the workpiece when it is of positive polarity. Thus, less amount of material is removed from the electrode during pulse on time. Material is not removed from the electrode during the pulse off time. Hence, pulse on time and pulse off time have very less contribution and significance to the electrode wear.

It is observed from Table 9 and Fig. 4 that the factors at level A_1 (discharge current, 10 A), B_3 (pulse on time, 65 μs), and C_3 (pulse off time, 48 μs) can be used to minimize RWR. Factors *A* and *B* are having significant effect for minimization of RWR, whereas factor *C* has least effect. It is observed from Table 13 that the contribution of pulse on time is more than the contribution of discharge current and pulse off time for RWR. The pulse on time decides the time duration of heat energy supplied to both workpiece and electrode. The electrode is exposed to less heat than the workpiece for the same time period when positive polarity is used. This causes less amount of material removal from an electrode as compared to the workpiece. The discharge current controls amount of heat energy required removing material from workpiece and electrode, hence its

Table 12 Results of the ANOVA for TWR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	*F* ratio	Contribution (%)	*P* value
A	Discharge current	2	91.28	45.64	33.32	91.74	0.001
B	Pulse on time	2	1.9	1	0.006	1.91	0.094
C	Pulse off time	2	4.3	3.5	0.35	10.47	0.087
Error		2	2.02			3.2	
Total		8	99.5			100	

Table 13 Results of the ANOVA for RWR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	*F* ratio	Contribution (%)	*P* value
A	Discharge current	2	12.93	6.46	1.64	35.41	0.026
B	Pulse on time	2	14.98	7.49	2.09	41.03	0.020
C	Pulse off time	2	4.93	2.47	0.47	13.5	0.065
Error		2	3.53			10.05	
Total		8	36.51			100	

Table 14 Results of the ANOVA for SR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	*F* value	Contribution (%)	*P* value
A	Discharge current	2	0.4	0.2	0.15	4.65	0.084
B	Pulse on time	2	7.23	3.61	15.74	84.07	0.005
C	Pulse off time	2	0.49	0.24	0.18	5.7	0.084
Error		2	0.48			5.58	
Total		8	8.6			100	

contribution and significance is more than pulse off time and less than pulse on time. The pulse off time shows least contribution and effect on RWR as no heat energy is supplied by the discharge current during this period.

From Table 10 and Fig. 5, factor *B* (pulse on time) is the most significant factor among all factors where as factors *A* (discharge current) and *C* (pulse off time) have insignificant effect on SR. The Table 14 indicates that the contribution of factor *B* is very high for SR as compared to factors *A* and *C*. The optimum level of factors for SR is A_1 (discharge current, 10 A), B_1 (pulse on time, 25 μs), and C_1 (pulse off time, 24 μs). The time duration of heat energy available for material removal depends on pulse on time. This energy is shared by a larger number of sparks results in reduction the size of the crater. This improves surface finish. Hence, contribution and significance of pulse on time is largest for SR.

It is interesting to note that optimal settings of parameters for SR and TWR are same but differs from optimal settings of parameters for MRR and RWR, and poses difficulty to achieve the target of all objectives.

3.2 Morphology of EDMed surface

The EDMed surface micrographs are shown in Fig. 6. It shows the overlapping craters, globules of debris, and pockmarks or chimneys, formed by entrapped gases escaping from the redeposited material. It is also observed that microcracks are present. They are formed due to development of high thermal stresses produced and plastic deformation of the material. In the EDM process, a large amount heat is generated during each spark. This heat is utilized to vaporize and melt the workpiece material as well as electrode material followed by rapid cooling by the dielectric fluid. This continuous rapid heating and followed by cooling resulted in a typical EDMed surface. When material is removed from the workpiece and electrode, craters are formed on their surfaces. During the flushing action, very less amount of removed material is carried away. The remaining material resolidifies to form an uneven surface.

Figure 6a–b indicates scanning electron microscope (SEM) for the optimum condition for MRR and SR respectively. It is observed that the size of craters, globules of debris, pockmarks or chimneys, and microcracks are larger in Fig. 6a due to higher discharge current (20 A) and longer pulse duration (65 μs). Thus, the surface is rougher as large amount of pulse energy is supplied for longer duration. Figure 6b shows smoother surface due to lower discharge current (10 A) and lower pulse on time (25 μs). At the low discharge current and smaller pulse duration, low amount of pulse energy is supplied for smaller duration. No craters, globules of debris, pockmarks or chimneys, and microcracks are observed. From Fig. 6b, the molten material is removed either by sheet formation or ligament formation. Proper removal material leads to smoother surface.

4 Conclusions

In this study, the influence of the process parameters and optimization of MDN 300 steel in the die sinking EDM was studied by using Taguchi method. From the results, it was found that discharge current, pulse on time, and pulse off time have been found to play significant role in EDM operations. Also, it was found that the optimal levels of the factors for SR and TWR are same but differs from the optimum levels of the factors for MRR and RWR. From

Table 15 Optimum values of the machining performance measures

Performance measure	Optimum condition	Optimum value
MRR (mm^3/min)	$A_3B_3C_2$	48.18
TWR (mm^3/min)	$A_1B_1C_1$	3.44
RWR	$A_1B_3C_3$	15.2
SR (R_a) (μm)	$A_1B_1C_1$	5.60

Table 16 Validation of the optimum results

Performance measure	Optimum condition	Optimum value	Experimental value
MRR (mm^3/min)	$A_3B_3C_2$	48.84	51.22
TWR (mm^3/min)	$A_1B_1C_1$	3.54	4.06
RWR	$A_1B_3C_3$	14.58	13.37
SR (R_a) (μm)	$A_1B_1C_1$	5.56	5.62

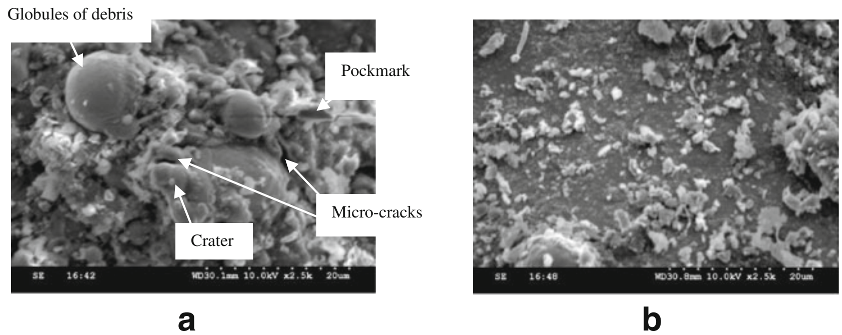

Fig. 6 SEM micrographs of MDN 300 steel; **a** optimum condition for MRR, **b** optimum condition for SR

ANOVA, discharge current is more significant than pulse on time for MRR and TWR; whereas pulse on time is more significant than discharge current for RWR and SR. On the other hand, pulse off time is less significant for all performance characteristics considered.

Surface morphological study indicates that at higher discharge current and longer pulse on duration gives rougher surface characteristics with more craters, globules of debris, and microcracks than that of lower discharge current and lower pulse on duration.

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