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Modeling the influence of WEDM Process Parameters on Material Removal Rate for Stainless Steel: RSM Parametric Study and Optimization

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Abstract. Wire electrical discharge machining (WEDM) is a precision machining method for cutting electrically conductive materials. It is an unconventional machining process that produces precision parts. The objective of the study is to investigate the impact of wire electrical discharge machining (WEDM) process parameters on the machining of stainless steel (SS304). These parameters are optimized to increase productivity by maximizing material removal rate (MRR). The factors that can affect the characteristics of machining or cutting in wire cut EDM process are wire tension (N), pulse time-off (μs), current (A), and voltage (V). The effect of these inputs parameters on the MRR response is analyzed and optimized using the response surface methodology (RSM) in the design of experiment (DOE) statistical method. The results from the RSM showed that the current (A) parameter had the most significant effect on the material removal rate.

Keywords: Unconventional cutting process, Wire Electrical Discharge Machining (WEDM), and Optimization.

Introduction

Machining processes play a significant role in manufacturing industry where cost and quality are the main driving forces. Among various manufacturing processes existing today, wire electrical discharge machining (WEDM) is one of the widely used processes because of its capability of machining intricate shapes and profiles irrespective of hardness of the material. This process finds widespread applications in mould-making tool and dies industries, aerospace, automobile and electronics industries [1]. WEDM has been found to be an extremely potential electro-thermal process in the field of conductive material machining [1]. The most important performance factors in study of WEDM are material removal rate (MRR), surface finish and cutting width (kerfs). They depend on machining parameters such as discharge current, pulse duration, pulse frequency, wire speed, wire tension, type of die electric fluid and dielectric flow rate. Selection of optimum machining parameter combinations for obtaining higher accuracy is a challenging task in WEDM due to the presence of a large number of process variables and complicated stochastic process mechanisms [1]. WEDM plays a significant role in cutting conductive materials to produce intricate profiles and complex shapes. The material removal occurs due to the melting and evaporation of the workpiece because of the heat produced by discharges. Numerically controlled systems regulate the wire traverse to accomplish the desired accuracy and precision of components. The most significant response variables in WEDM are the material removal rate (MRR) and surface roughness (SR) of the workpiece [2].

Sharma et al. [3] investigated the effect of parameters on the metal removal rate and surface roughness for WEDM using HSLA as a workpiece and brass wire as electrodes. The parameters were pulse on time, peak current, pulse off time, and servo voltage. Response Surface methodology (RSM) is used to optimize the process parameter for metal removal rate and surface roughness. RSM is formulating a mathematical model that correlates the independent process parameters with the desired metal removal rate and surface roughness. The central composite rotatable design (CCRD) has been used to conduct the experiments. They found metal removal rate and surface roughness increase with the increase in pulse on time and peak current. Metal removal rate and surface roughness decrease with an increase in pulse-off time and servo voltage. Srivastava et. al. [4] presented an experimental study on a composite of Al2024 reinforced with SiC to investigate the effects of electric discharge machining(EDM) for three levels of each parameter such as current, pulse on time, and reinforcement percentage on surface finish and material removal rate (MRR). The response surface methodology (RSM) technique has been applied to optimize the machining parameters for minimum surface roughness and maximum MRR. As a result, surface roughness was increased with the increased peak current, pulse on time, and reinforcement. The material removal rate was increased with peak current and pulse on time and decreased with the increase in enforcement.

Priyan et. al. [5] studied the cutting performance by varying parameters such as pulse on time, pulse off time, servo voltage, wire feed, current, and cutting speed. The tools and work materials used were brass wire and SS 304. The output parameters studied were material removal rate (MRR) and surface roughness. The experimentation was completed using Taguchi's L16 orthogonal array under different conditions of parameters. The results showed that the increase in pulse on time generated more spark energy. The MRR, Kerf width, and surface roughness responded by increasing with pulse on time. Among all the responses, pulse on time was found to be the most significant parameter. Surface roughness also increased with the increase of pulse on time. This was because the increase in pulse on time produced deeper and broader craters. On the other hand, pulse off time had the opposite effect to pulse on time. The MRR decreased with the increase of pulse-off time, while surface roughness reduced. During the rest period, the removed material was discarded. The more rest time given, the better the cleaning. Servo voltage had little effect on SR and KERF width, but it had more effect on MRR. Surface roughness decreased while increasing the servo voltage. Sivaprakasam et al. [6] investigated nano-powder mixed Micro-Wire EDM process of Inconel-718 alloy. Machining parameters such as voltage (A), capacitance (B), powder concentration (C), The performance of experiment were material removal rate (MRR), kerf width (KW) and surface roughness (SR). Twenty-seven experiments were carried out based on full factorial design by varying voltage, capacitance and powder concentration each at three levels. Data were analysed using software. The experiment showed that adding graphite nanopowder to the dielectric improved the topography and roughness of the machined surface significantly. Particularly, the (Ra) values reduced from 0.830 mm to 0.418 mm, and the material removal rate increased to 0.0055 mm^3/min. These changes resulted in a higher material removal rate and better surface quality.

Goyal et. al. [7] employed zinc-coated brass wire electrode for enhanced machining speed, accuracy, and precision, to investigate the variation in process parameters such as peak current (Ip), pulse on time (Ton), pulse off time (Toff), and feed rate (FR) with optimization during WEDM machining operation. The obtained results have been optimized by Taguchi’s methodology. They found that surface roughness increases with a decrease in pulse-off time and spark gap set voltage. The surface roughness on the sample was enhanced with an increase in (Ton) and (IP). Chakraborty et.al. [8] focused on enhancing the die corner accuracy of Ti6Al4V by using mixed wire EDM powder and also investigated the effect of process parameters such as peak current, pulse operation, pulse off time and powder types and response measures such as die corner error and material removal rate by using the Taguchi methodology. From the experiment, it was found that a 43.66% improvement in angle accuracy was achieved in the proposed hybrid technique. The MRR was affected by the peak and pulse current in time followed by the powder species. It was the best choice for advanced material machining to achieve better dimensional accuracy in angle machining than using multiple processes such as cut-off, path adjustment, and parameter adjustment. In powder mixed wire EDM, a lower pulse set was preferred as energy consumption was lower and productivity was higher with high precision dimensions. Among all types of powders used, B4C abrasive powder particles mixed with dielectrics play the most important role in angle error and MRR. Sharma et.al. [9] investigated the characteristics of AISI D2 die steel of 13 mm diameter was performed using a 0.25 mm diameter wire electrode. The influence of various input process parameters pulse on time (Ton), pulse off time (Toff), peak current (Ip), and wire tension(Tw), on the response characteristics metal removal rate (MRR) and machining time (MT) were investigated by using Taguchi L9 orthogonal array. Signal-to-noise ratio and ANOVA were also employed in the study of response parameters. They found (T_{off}) has been the leading significant factor for MRR, gap current, and time taken for machining due to the fact that the difference between the result values for all three levels was quite higher than the other machining parameters. Larger variation leads to a delta value which defines the gap between the largest and smallest response value of each parameter. Therefore, this study aims to analyze and optimize the effect of WEDM cutting process parameters on the material removal rate (MRR) of (SS304) stainless steel using response surface methodology(RSM),.

Experimental Details

Material Selection:

Stainless steel (SS304) was used in this study. Stainless steels are described as steel alloys with a high chromium content, great strength, and resistance to corrosion as their primary characteristics. Storage tanks and tankers used to transport orange juice and other foods are often made of SS due to their corrosion resistance and antibacterial properties. This also influences its use in commercial kitchens and food processing plants, as it can be steam cleaned, and sterilized and does not need painting or the application of other surface finishes [10]. The chemical composition of SS 304 is shown in Table 1. The mechanical and physical properties are shown in Tables 2 and 3, respectively.

Table 1: The chemical composition of Stainless Steels SS304

Compst.	wt %
Cr	20
Ni	10
Mn	2
C	0.08
Si	*0.75*
P	*0.045*
S	*0.03*
N	*0.1*
Fe	*Balance*

Table 2: Mechanical properties of the base material

Mechanical Properties	Metric	English
Ultimate Tensile Strength	520 MPa	73200 psi
Tensile Yield Strength	210MPa	31200 psi
Hardness (Rockwell B)	70	70
Modulus of Elasticity	193 GPa	28000-29000 ksi

Table 3: Physical properties of the base material.

SS 304	
Density	7.93 g/cm^3
Melting Point	1723 K
Specific Heat	530 J/Kg. K
Thermal Cond.	16.2 W/ m. K

Cutting Machine Used

This study was carried out utilizing a type (ONA UE / RE 250) machine (Fig. 1). The material of the electrode is Cu 63% / Zn 37% and the diameter is 0.25 mm, and used in the machine is Aircut 7.1 Wire EDM CNC System. This machine Provided by Arabian Golf Oil Company (AGOCO), Benghazi, Libya

Fig. 1: the used ONA Electro-Erosion Machine

Experimental Design:

Statistical design has been carried out on the data obtained from the experiments designed using the RSM. The Center Composite Design (CCD) approach is adopted in this research. The selected input variables for the analysis of MRR were wire tension, time off, current, and voltage. Next, the Design of Experiments (DOE) planning was performed using a 3-level consisting of 30 runs, and 4 factors with one responses. Based on trial runs and literature review the fixed process parameters are: Dielectric conductivity: 17mho, servo voltage: 15V, dielectric feed: 5V/min, and wire feed rate: 6m/min, and the levels of the factors are determined and shown in Table 4.

Table 4: the factors levels for input parameters

Parametric	Coded	Level -1	Level 0	Level 1
Wire Tension (N)	A	16	18	20
Time off (µs)	B	3	4	5
Current (A)	C	4	6	8
Voltage (V)	D	130	145	160

After setting up and inputting the factors levels for each variable into the program, experiments were carried out according to this design, then the material removal rate response is obtained and filled in the RSM design matrix. Table 5 displays the Design Matrix for WEDM with the MRR response keyed in.

2.4. Material Removal Rate MRR

For (WEDM) MRR is a desired characteristic and should be as high as possible to give less machine cycle time leading to increased productivity in the present study. MRR is calculated by using Eq1, (Sharma, et al.,2013) [3]:

$$MRR = F.\,D.\,H \tag{1}$$

Where:
MRR = Material removal rate (mm^3/ min),
F = Cutting speed (mm/min),
D = Diameter of wire (mm),
H = Thickness of workpiece (mm).

2.5. Details of Experimental Samples

The sample of SS-304 used in this study was 5.55 mm thick and 85 mm in diameter. Fig 2 shows the sample before the cut. The " NX12 " program divided thirty experiments equally on the circumference and inside the circle, with the length of the cut in each experiment being 21.79 mm. Fig 3 shows the experiments on the sample. In addition, the CNC system "Ajax milling machine" numbered the experiments on the working sample.

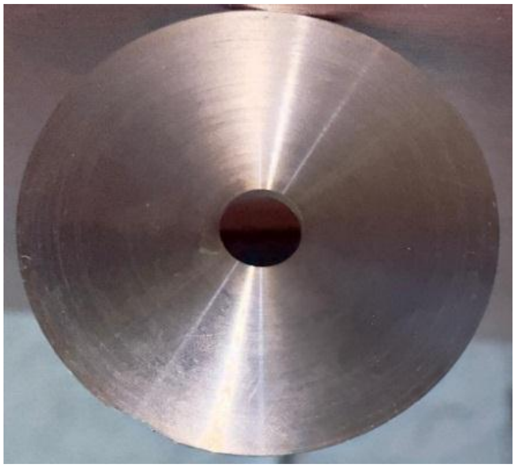


Fig 2: Base material

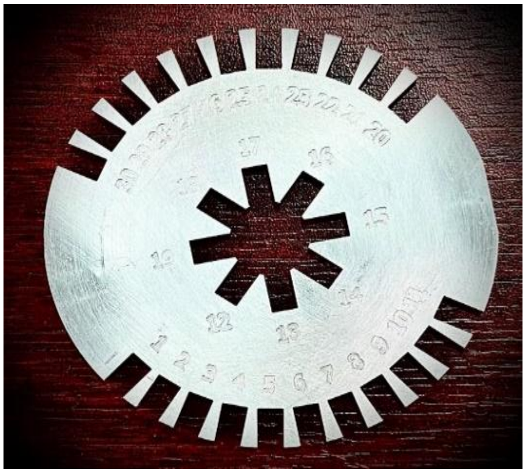


Fig 3: View the cut on material

Table 5: The Completed WEDM RSM Design Matrix

Run	Wire Tension (N)	Time off (µs)	Current (A)	Voltage (V)	MRR(mm³/min)
1	16	3	4	160	1.110
2	20	4	4	130	0.950
3	18	4	6	145	1.721
4	20	4	6	145	1.790
5	16	5	8	160	3.004
6	16	4	4	160	1.145
7	18	3	6	160	2.081
8	20	3	8	160	3.288
9	20	4	4	130	0.937
10	16	3	8	160	3.164
11	20	5	8	130	3.510
12	20	4	4	160	1.318
13	18	5	6	145	1.804
14	16	5	4	130	0.930
15	18	5	4	145	1.159
16	16	3	8	130	3.261
17	20	3	8	160	3.427
18	18	5	6	160	1.943
19	20	5	4	160	1.221
20	18	4	6	130	1.665
21	20	4	8	130	3.177
22	20	5	6	145	1.908
23	18	4	8	145	3.448
24	18	3	6	145	1.859
25	16	5	8	130	3.275
26	16	4	6	145	1.797
27	20	3	4	130	0.957
28	16	5	6	160	1.776
29	20	3	6	160	1.929
30	16	3	6	145	1.790

Result and Discussion

The MRR was calculated using equation (1), indicating varying MRR values for different parameters. From the table 5, the maximum MRR is 3.51 mm³/min, when the WT= 20 N, Time-off= 5µs, current= 8A, and voltage= 130 V. The minimum MRR is 0.930 mm³/min, when the WT= 16N, Time-off= 5 µs, current= 4A, and voltage= 130 V. However, comprehensive statistical analysis is performed in details hereafter.

Rresults and Analysis for MRR

Analysis of the effects on the cutting parameters in more detail was carried out using analysis of variance (ANOVA) with implementing the regression method using software. The analysis results for the reduced linear model, which is suggested by the software for the calculated MRR values are shown in Table 7. If the "P" value is less than 0.0001, the corresponding factor is said to have a significant influence on the response, at a 99.9% confidence level. Also, a high "F" value for a parameter means that the parameter effect on the joint's characteristics is large. As the Table shows, factors A significantly influence the (MRR). Furthermore, C (current) was the most significant factor. A Lack of Fit F-value this large could occur due to noise 35.67% of the time, indicating a minor lack of fit. Also, [3] and [12] found that MRR increases with the increase in peak current.

Table 7: ANOVA for MRR

MRR analazyd					
Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	23.05	14	1.65	166.66	< 0.0001 significant
A-Wire Tension	0.0688	1	0.0688	6.96	0.0186
B-Time off	4.83E-06	1	4.83E-06	0.0005	0.9827
C-Current	19.6	1	19.6	1983.64	< 0.0001
D-Voltage	0.0613	1	0.0613	6.21	0.0249
AB	0.003	1	0.003	0.308	0.5871
AC	0.0006	1	0.0006	0.0564	0.8154
AD	0.007	1	0.007	0.7055	0.4141
BC	0.0009	1	0.0009	0.0935	0.764
BD	0.0112	1	0.0112	1.13	0.3036
CD	0.0355	1	0.0355	3.6	0.0773
²	0.0208	1	0.0208	2.11	0.1672
B^2	0.0088	1	0.0088	0.8924	0.3598
C^2	0.643	1	0.643	65.09	< 0.0001
D^2	0.001	1	0.001	0.103	0.7527
Residual	0.1482	15	0.0099		
Lack of Fit	0.1385	13	0.0107	2.19	0.3567
Pure Error	0.0097	2	0.0049		
Cor Total	23.2	29			

Table 7 also shows the value of R-squared (R^2), adjusted R-squared (Adj. R^2), and predicted R-squared (Pred. R^2) statistics. The R^2 value indicates the adequacy of the suggested model. The higher the R^2 value, the better the model fits the experimental data, which is that R^2 is always between 0 and 100%. [12]. The results obtained for MRR demonstrated that the R-squared value (0.9936), which approaches 1, is desirable. Pred-R^2 determines how well the model predicts responses for new observations. Larger values of Pred-R^2 indicate models of greater predictive ability. The predicted R^2 of 0.9702 is in good agreement with the adjusted R^2 of 0.9877. This is consistent with [13] findings the difference between the adjusted and predicted R^2 is less than 0.2. The Adeq precision value > 4 is desirable for computing the signal-to-noise ratio.

Mathematical Model of MRR

The mathematical model for MRR has been developed by linear-interaction regression analysis. The mathematical equation for MRR has been expressed in terms of the process variables cutting wire tension (A), time off (B), current (C), and voltage (D) in the form. A mathematical equation for MRR has been developed by linear-interaction regression analysis. The mathematical equation for MRR has been expressed in terms of the process variables cutting wire tension (A), time off (B), current (C), and voltage (D) in the form. Eq2 explain the output response (y) can be modelled as:

$$y = \beta 0 + \sum_{i=1}^{k} \beta i \ x i + \sum_{i=1}^{k} \beta ii \ x^2 i + \sum_{i<j}^{k} \beta ij \ x i \, x j + \varepsilon \qquad (2)$$

Where xi, xj and xk are input or independent process parameters.

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space. The final mathematical model to estimate MRR in terms of actual factors is given as Equation 3:

-5.17484 +0.431435 (WT) -0.235009 (PT) -0.298486 (C) +0.031587 (V) +0.011441(WT * PT) +0.002015 (WT * C) +0.001144 (WT * V) +0.007070 (PT * C) -0.002487 (PT * V) -0.002657 (C * V) -0.017359 (WT^2) +0.043340 (PT^2) +0.097174 (C^2) -0.000077 (V^2)ccc (3)

Where, WT: wire tension, PT: pulse time –off, C: current, and V: voltage

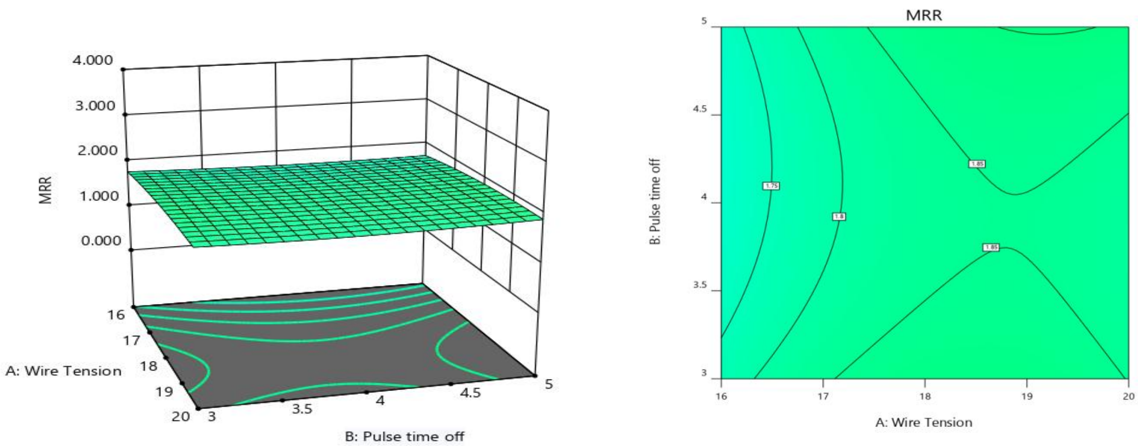
Accordingly, the final regression model in terms of coded factors for predicting MRR is presented in Equation 4:

MRR = 1.84 + 0.0604*A – 0.0005*B +1.09*C + 0.0605*D + 0.0229*AB + 0.0081*AC + 0.0343*AD + 0.0141*BC – 0.0373*BD – 0.0797*CD – 0.0694 *A^2 + 0.0433*B^2 + 0.3887*C^2 - 0.0173*D^2 (4)

Three Dimensional Surface and Contour Plots of MRR

Three-dimensional surface (3D) plots are commonly used to predict the MRR response value at a given combination of two parameters, with the remaining parameters held constant. These plots indicate the degree of combination effect on the response variables, with more curvature, bend, or undulations indicating a stronger effect. On the other hand, straight contour lines in (2D) contour plots suggest a weaker combination effect, while more bending or curving lines indicate a stronger effect. The contour plots are particularly useful when the stationary point is outside the design region or a saddle. It is important to note, however, that the extent of combination effects varies and is not the same in all cases. The (3D) surface and contour plots for MRR are presented in Figs (4-9).

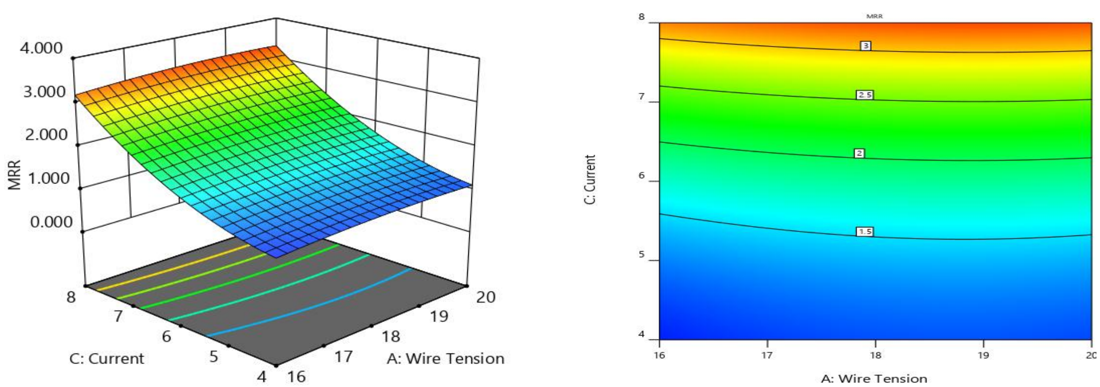
In Fig. 4 (a) when the wire tension (A) and the pulse time-off (B) change, the combined effect on the MRR is shown in plots despite the current (C) and voltage (D) remaining constant. However, Fig.4(b) the effect of the combination is less significant. This shows that the combined change in wire tension and pulse time-off does not significantly affect MRR.



(a) (b)

Figs. 4 (a and b): plots showing combined effects of A and B on MRR (mm³/min) when C and D are kept constant at (6A and 145V)

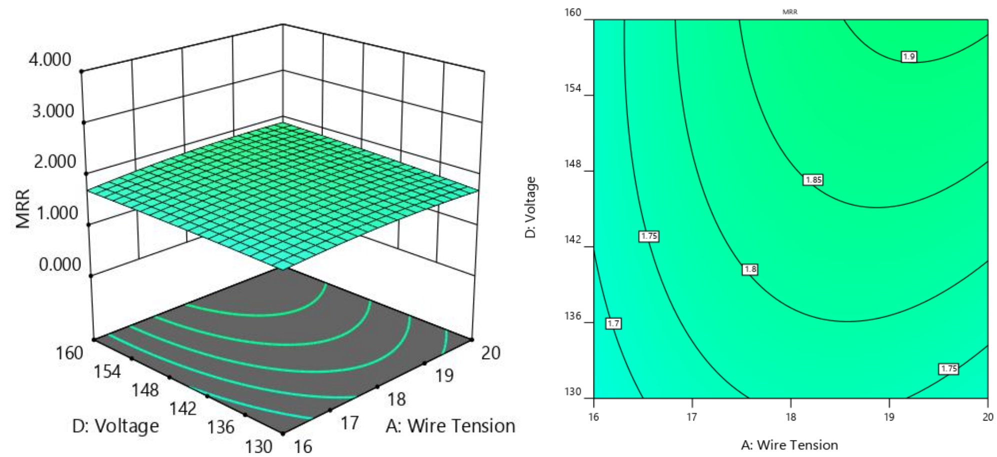
In Fig 5(a) the curvature in the response is very distinct, indicating that the combined effect of wire tension (A) and current (C) on MRR is significant. Response surface plots, as mentioned earlier, can be used to predict the response value for a given combination of any two factors. At the same time, the remainder parameter is held at a constant level. The MRR increases when the wire tension (A) increases with the higher current (C). The MRR values do not affect when reducing the wire tension (A) in the higher current (C), while the pulse time-off (B) and voltage (D) are held constant. In Fig. 5(b) shows that the combined change in wire tension and current significantly affects MRR, when the current is at its highest value.



(a) (b)

Figs. 5 (a and b): plots showing combined effects of A and C on MRR (mm³/min) when B and D are kept constant at (4μs and 145V)

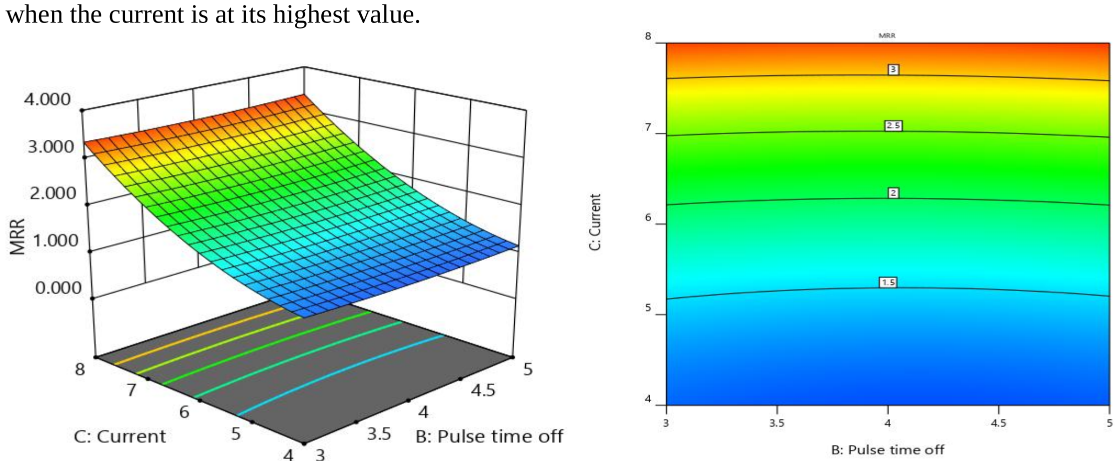
Fig. 6(a) is a plot showing the combined effects of wire tension (A) and voltage (D) on MRR when pulse time-off (B) and current (C) are kept constant. The effect is less pronounced when these factors are combined. Fig. 6(b) shows that the combined change in wire tension and voltage does not affect MRR.



(a) (b)

Figs. 6 (a and b): plots showing combined effects of A and D on MRR (mm³/min) when B and C are kept constant at (4µs and 6A)

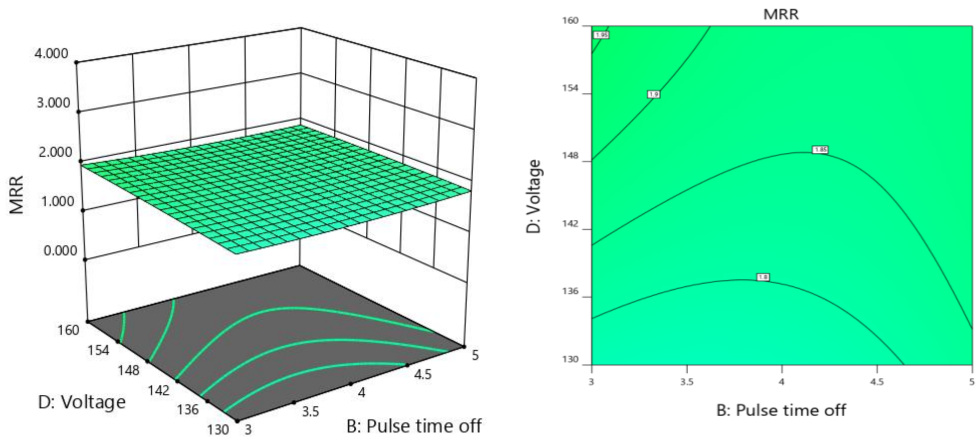
Fig. 7(a) is a plot showing the combined effects of pulse time-off (B) and current (C) on MRR while wire tension (A) and voltage (D) are held constant. The combined effect of pulse time-off (B) and current (C) on MRR is significant. In Fig. 7(b) shows that the combined change in pulse time-off and current has a clear effect on MRR, when the current is at its highest value.



(a) (b)

Figs. 7 (a and b): plots showing combined effects of B and C on MRR (mm³/min) when A and D are kept constant at (18N and 145V)

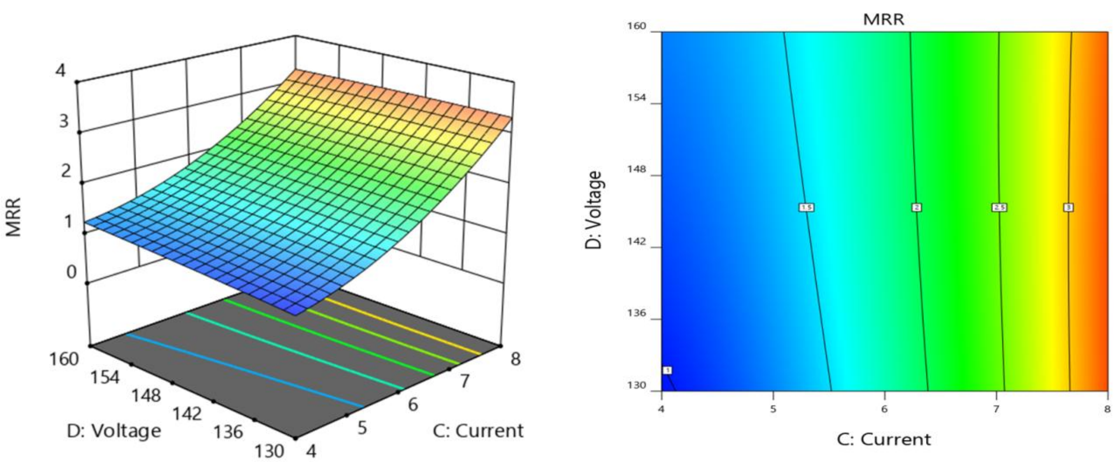
Fig. 8 (a) shows the combined effects of pulse time-off (B) and voltage (D) on MRR while wire tension (A) and current (C) are held constant. The effect is less pronounced when these factors are combined. In Fig. 8(b), when these factors are combined, the effect is less noticeable. MRR is unaffected by the combined change in pulse time-off and voltage.



(a) (b)

Figs. 8 (a and b): plots showing combined effects of B and D on MRR (mm³/min) when A and C are kept constant at (18N and 6A)

Fig. 9(a) shows the combined effects of current (C) and voltage (D) on MRR while wire tension (A) and pulse time-off (B) are held constant. The combination effect of current (C) and voltage (D) on MRR is significant. Also, the contour plots indicate that a combination of current (C) and voltage (D) has a prominent effect on MRR. In the same manner, interpretations may be made from the other plots as well. In Fig. 9(b), when these factors are combined, they affect MRR, when the current is at its highest value.



(a) (b)

Figs. 9 (a and b): plots showing combined effects of C and D on MRR (mm³/min) when A and B are kept constant at (18N and 4μs)

MRR Optimization plot

The optimization plots shown in Fig. 10 represents the influence of each parameter on the MRR response. The developed model was used for optimizing the cutting input parameters. Optimization was calculated for each parameter separately without considering the other parameters. This is to convene practical for MRR. The achieved results were based on the different criteria presented in Table 8. In the same table, the selected importance of each factor is present. The selected importance greatly affects the result, and it is essential to select it correctly. The numerical optimization results based on MRR response calculation are presented in Table 9.

Table 8: The optimization criteria for input/output cutting parameters

Parameters / Response	Criteria	Importance
Wire Tension	Range	+++
Time-off	Range	+++
Current	Min	+++
Voltage	Min	+++
MRR	Max	+++++

Table 9: The numerical optimization results based on material removal rate (MRR) response

Responses	Parameters				
	Wire tension (N)	Pulse time-off (µs)	Current (A)	Voltage (V)	Response Value
MRR (mm^3/min)	18.78	5	7.33	130	2.818

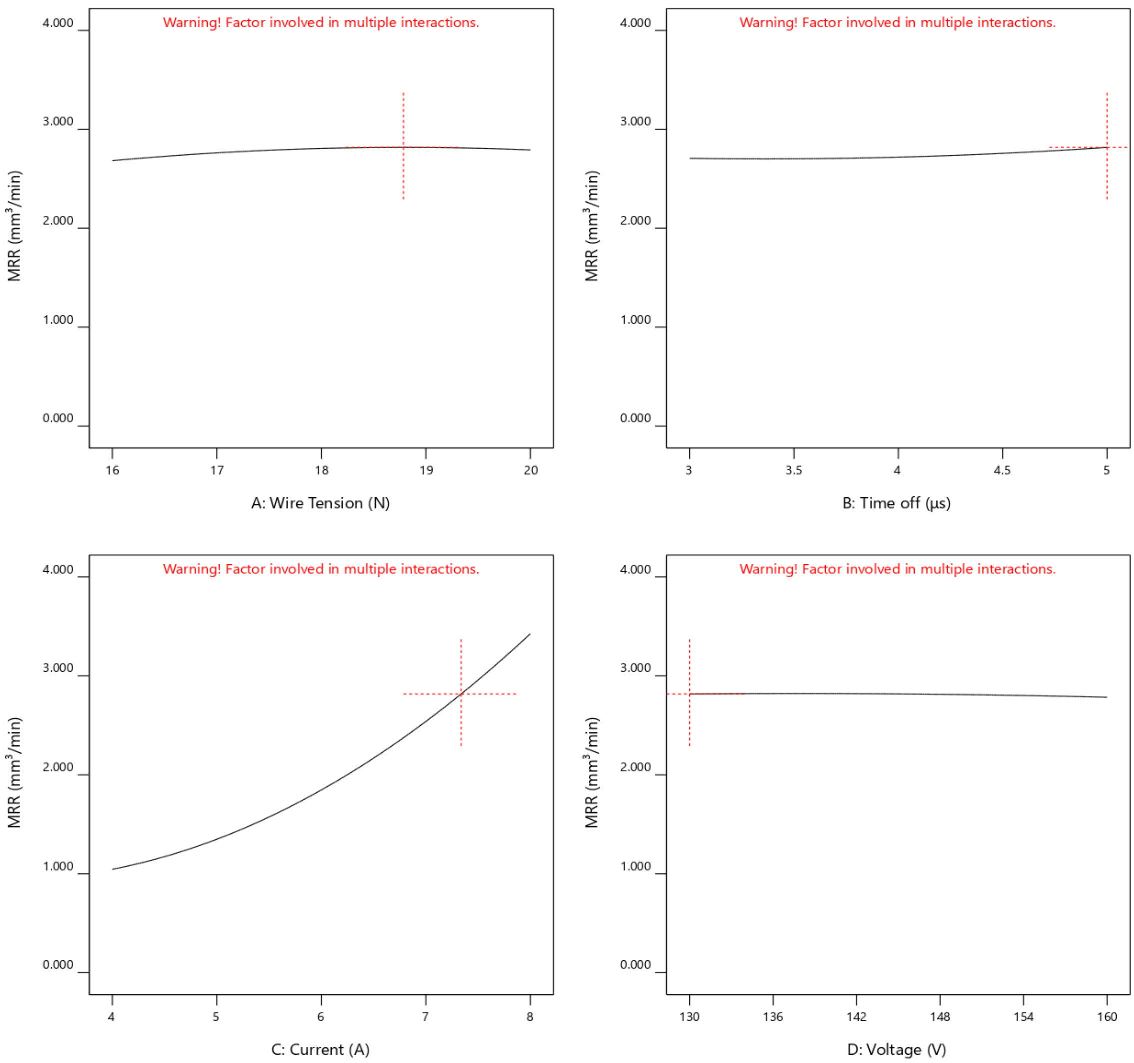


Fig. 10: MRR Optimization plots

Conclusions

In the present research work for the wire-cutting process of SS304 stainless steel, the response was material removal rate (MRR). Based on the results of the experiments, modeling, and analyses conducted in this study, the main conclusions are presented in the following points:

1. Using a Design of Experiment inspired by the RSM approach, achieving the best operating parameter window and developing models to control the cutting parameters is possible.
2. The models achieved using RSM for (MRR) can adequately mathematically predict the responses within the factors domain
3. From the experiment, it was concluded that increasing current increases the feed rate, affecting on MRR
4. The model performed using RSM between cutting parameters and MRR of SS-304 stainless steel is acceptable due to the 84.26% of the actual data described by the model.
5. The ANOVA show that the current was the most significant factor. Pulse time-off was not found to be a very important factor influencing MRR.
6. The RSM method using software, the optimum parametric setting predicted by the model that given the optimum values of maximum (MRR) obtained under wire tension = 18.78, pulse time-off = 5μs, current = 7.33A, and voltage= 130V.

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