WEDM Process Parameters Analysis for Stainless Steel: Full Factorial Design of Experiment Screening

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Abstract:

The objective of the study is to perform a full factorial design investigation as a first Screening stage for the effect of wire electrical discharge machining (WEDM) process parameters on the machining of stainless steel (SS304). This step was found to be very essential in this research work. The reason was the wide scattering of cutting parameters ranges available in the literature. Therefore, there was no clear picture on the suitable parameters ranges which should be taken in a comprehensive DOE analysis using more advanced methods such as the Response Surface Methodology (RSM) or the Taguchi Method. The material removal rate (MRR) was chosen as a response in this study. The factors considered are: wire tension (N), wire feed (mm/s), current (A), and voltage (V). Basic factors ranges were chosen based on the literature review, and then a full factorial design is generated and WEDM cutting experiments were carried out accordingly. Then statistical analysis is performed and parametric study and optimal settings for achieving maximum material removal rate value was determined. The results from the full factorial design showed that the current (A) parameter had the most significance on the material removal rate.

Keywords: Index Terms - Unconventional cutting process, WEDM, DOE, full factorial design, Optimizations.

الملخص

الهدف من هذه الدراسة هو إجراء تحقيق تصميم مضاعف كامل كمرحلة فرز أولى لتأثير معلمات عملية القطع التفريغ الكهربائي السلكي (WEDM) على تصنيع الفولاذ المقاوم للصدأ(SS304) . وُجد أن هذه الخطوة ضرورية للغاية في هذا العمل البحثي. والسبب هو التشتت الواسع لنطاقات معلمات القطع المتاحة في الأدبيات .ولذلك، لم تكن هناك صورة واضحة حول نطاقات المعلمات المناسبة التي يجب أخذها في تحليل تصميم التجارب الشامل باستخدام طرق أكثر تقدمًا مثل منهجية

سطح الاستجابة(RSM) أو طريقة تاغوتشي. تم اختيار معدل إزالة المواد (MRR) كاستجابة في هذه الدراسة. العوامل التي تم أخذها في الاعتبار هي: شد السلك(N) ، وتغذية السلك (مم/ثانية)، والتيار(A) ، والجهد .(V) تم اختيار نطاقات العوامل الأساسية بناءً على مراجعة الأدبيات، ثم تم إنشاء تصميم مضاعف كامل وتم إجراء تجارب قطع WEDM وفقًا لذلك. ثم تم إجراء تحليل إحصائي ودراسة بارامترية وتحديد الإعدادات المثلى لتحقيق أقصى قيمة لمعدل إزالة المواد. أظهرت النتائج من التصميم المضروب الكامل أن المعلمة الحالية شدة التيار (A)كان لها الأهمية الأكبر على معدل إزالة المواد.

الكلمات المفتاحية: الطرق غير التقليدية للتصنيع، التصنيع بالتفريغ الكهربائي , تصميم التجارب, التصميم المضاعف الكامل , التحسين)

Introduction

Machining involves the removal of some material from the workpiece to produce a specific geometry at a definite degree of accuracy and surface quality. Parts manufactured by casting, forming, and various shaping processes often require further operations before being ready for use or assembly. In many engineering applications, parts have to be interchangeable to function correctly and reliably during their expected service lives thus, control of the dimensional accuracy and surface finish of the parts is required during manufacture. (El-Hofy, 2005)

Electrical Discharge Machining, (EDM) is capable of machining complex shapes with the most accuracy. In EDM machining is done by eroding the material by electrical discharge forming an arc between the workpiece and tool electrode. In wire-cut electrical discharge machining (WEDM) or commonly called wire EDM, a wire as an electrode is used. The wire electrode discharges a huge amount of spark to the metal workpiece. A thin film of fluid mostly a dielectric fluid separates the workpiece and wire electrode and wash away the debris produced. The accuracy during WEDM process is obtained by numerically controlled axis movement of wire electrode holder (Mahapatra and Patnaik 2007, Sharma and Vates 2021). Fig. 1 shows the WEDM process and essential elements.

The most significant response variables in WEDM are the material removal rate (MRR) and surface roughness (SR) of the workpiece (Bobbili et al 2015).

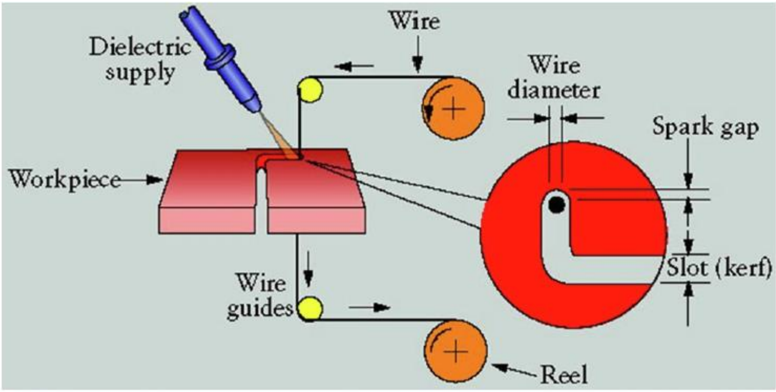


Fig. 1. Schematic diagram of Wire EDM system (Bobbili et al 2015)

In reviewing some of the previous research work in this issue, Sharma et. Al, 2013) 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. (2014), 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. Swin et al. (2016) investigated 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 carried out 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. (2019) 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. (2021), 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. (2021), 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 their experiments, 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 (2021) investigated the characteristics of WEDM cutting of AISI D2 die steel of 13 mm diameter using a 0.25 mm diameter wire electrode. The influence of various input process parameters such as pulse on time (Ton), pulse off time (Toff), peak current (Ip), and wire tension(Tw), on the metal removal rate (MRR), Ig and machining time (MT) were investigated by using Taguchi L9 orthogonal array. Signal-to-noise ratio and ANOVA analysis were employed in the study of response parameters. They found that (Toff) was 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.

Therefore, this study aims to provide a basic full factorial screening which would be considered as a first step in a more comprehensive analysis and optimization using another more advanced analysis methods. Therefore, effect of WEDM cutting process parameters on the material removal rate (MRR) of (SS304) stainless steel is the main target of this research work.

1. Experimental Details

2.1 Material Selection

Stainless steel (SS304) was selected 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 (Youssef, 2015). The measured chemical composition of SS 304 is shown in Table 1. The mechanical and physical properties of SS304 are shown in Tables 2 and 3, respectively.

Table 1: The chemical composition of SS304 (Measured)

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 SS304 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

2.2. Type of Cutting Machine Used

This study was carried out utilizing a type (ONA UE / RE 250) machine. 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 (See Fig.2). This machine provided by Arabian Golf Oil Company (AGOCO), Benghazi, Libya**.**

Fig. 2: ONA Electro-Erosion Machine (Availeble at the Araian Gulf Oil Company Central Workshop, Ganfooda , Benghazi)

2.3. Material Removal Rate (MRR) Calculation

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 Eq. (1), (Sharma at al, 2013):

$$MRR = F.\ D.\ H \qquad (1)$$

Where:

MRR = Material removal rate (mm³/min),

F = Cutting speed (mm/min),

D = Diameter of wire (mm),

H = Thickness of workpiece (mm).

2.4. The Full Factorial Experimental Design

The experimental work was designed according to the full factorial design of experiment methodology as a first screening stage in this WEDM study. This step was found to be very essential in this research work. The reason was the wide scattering of cutting parameters ranges available in the literature. Therefore, there was no clear picture on the suitable parameters ranges which should be taken in a comprehensive DOE analysis using more advanced methods such as the Response Surface Methodology (RSM) or the Taguchi Method. The selected input variables for the analysis of MRR were wire tension, wire feed, current, and voltage. Next, the factorial design was performed using a 2-level consisting of 8 runs, and 4 factors with one responses. The levels of the factors was selected based on trial WEDM runs and literature, and are as shown in Table 4. The fixed process parameters are Dielectric conductivity: 17mho, servo voltage: 15V, and dielectric feed: 5V/min. In addition, Table 5 displays the completed design matrix for WEDM cutting process.

Table 4: the factorial design levels of the factors

Parametric	Coded	Level -1	Level 1
Wire Tension (N)	A	16	20
Wire feed (mm/s)	B	100	130
Current (A)	C	4	8
Voltage (V)	D	130	160

Table 5: The Design Matrix with the MRR Response Keyed in.

Run	WT (N)	WF(mm/s)	C(A)	V(V)	MRR(mm³/min)
1	20	100	8	130	0.99
2	16	130	4	160	0.79
3	20	130	4	130	0.84
4	20	130	8	160	1.25
5	16	130	8	130	0.95
6	20	100	4	160	0.74
7	16	100	8	160	1.24
8	16	100	4	130	0.85

3. Result and Discussion

The MRR in the WEDM process is essential because of its vital effect on the industrial economy. The MRR was calculated using equation (1), indicating varying MRR values for different parameters. In general, from the Table 5, the maximum MRR was 1.24 mm³/min, when the WT= 20N, wire feed = 130 mm/s, current= 8A, and voltage= 160 V, and the minimum MRR was 0.930 mm³/min, when the WT= 20N, wire feed = 100 mm/s, current= 4A, and voltage= 160 V. However, a more detailed statistical and graphical analysis is provided hereafter.

3.1. MRR Results Analysis of Variance

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 Minitab software. The ANOVA results for the reduced linear regression model, which is suggested by the software for the calculated MRR values are shown in Table 7. If the "P" value is less than 1% (Based on 90% confidence interval), the corresponding factor is considered to have a significant influence on the response. Also, a high "F" value for a parameter means that the parameter effect is large. As the Table shows, even though the strict 1% criteria could not be achieved for all factors. However, the C (current) was the most significant factor.

Table 7: ANOVA for MRR Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.241232	0.040205	3.12	0.408
Linear	4	0.161302	0.040325	3.13	0.398
WT	1	0.001328	0.001328	0.10	0.802
WF	1	0.009859	0.009859	0.77	0.542
C	1	0.145982	0.145982	11.35	**0.184**
V	1	0.018489	0.018489	1.44	0.443
2-Way Interactions	2	0.043621	0.021810	1.70	0.477
WT*WF	1	0.025091	0.025091	1.95	0.396
WT*C	1	0.005706	0.005706	0.44	0.626
Error	1	0.012866	0.012866		
Total	7	0.254098			

Model Summary

S	R-sq	R-sq(adj)
0.113430	94.94%	64.56%

Table 7 also shows the value of R-squared (R^2), and adjusted R-squared (Adj. 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% (Lakshmikanth et al, 2013, Minitab Statistical Software). The results obtained for MRR demonstrated that the R-squared value (0.9494), which approaches 1, is desirable with the adjusted R^2 of (0.6456). Therefore, the generated MRR model is reasonably acceptable and could be used as a first screening guide to further analysis in the WEDM for 304 stainless steel. In the following sections, the model and its graphical output are presented.

3.2. Mathematical Model of MRR

The developed egression mathematical equation for MRR has been expressed in terms of the process variables cutting wire tension (A), wire feed (B), current (C), and voltage (D) in the form. The mathematical model for MRR has been developed by linear-interaction regression analysis. Eq. (2) explain the output response (y) can be modelled as:

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

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

The model in terms of actual factors can be used to predict the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. The final mathematical model to estimate MRR in terms of actual factors is given as shown in Eq. (3):

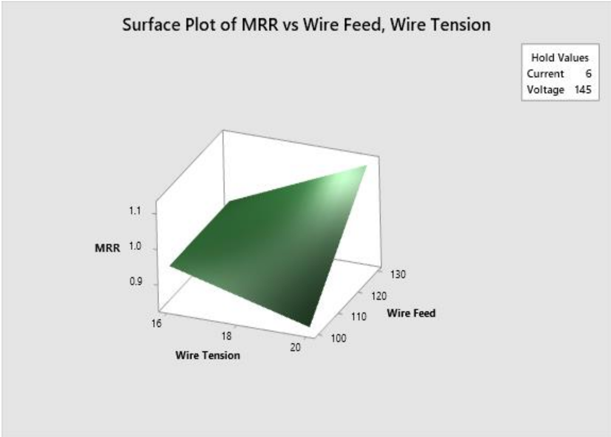
*MRR = 4.53 - 0.304 Wire Tension - 0.0365 Wire Feed - 0.064 Current + 0.00600 Voltage+ 0.00229 Wire Tension*Wire Feed + 0.0082 Wire Tension*Current* (3)

3.3. MRR 3D Surface and Contour Plots

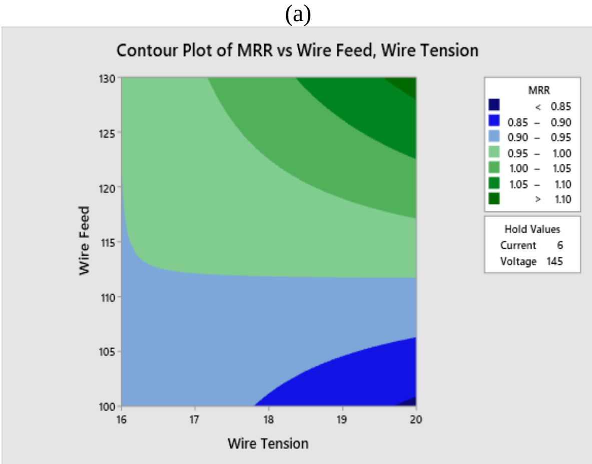
Based on the MRR mathematical model, a 3D surface and contour plots were then generated for each pair of two parameters, with the remaining parameters held constant. These plots indicate the degree of combination effect on the response variables. For the 3D surface plots, the more curvature, bend, or undulations indicating a stronger effect. In the same regard, 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. The (3D) surface and contour plots for MRR are presented in Figs (3 to 8).

Figs. 3 (a & b) shows that when the wire tension (A) and the wire feed (B) change, the combined effect on the MRR is significant shown in plots despite the current (C) and voltage (D) remaining constant. The MRR increases when the wire tension (A) increases in the higher wire feed (B) and MRR decreases when the wire tension (A) increases in the lower wire feed (B).

Figs. 4(a & b), shows that the twist in the response is very distinct, identifying that the combination 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 at a given combination of any two factors.

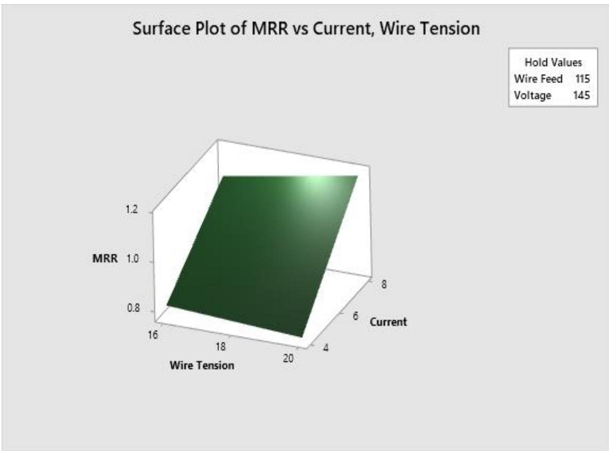


(a)

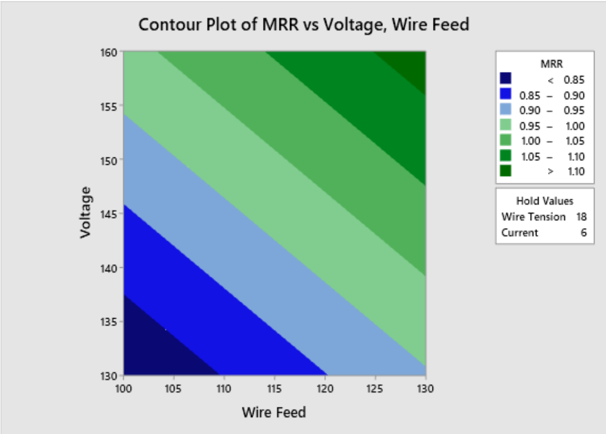


(b)

Figs. 3 (a & b): effects of A and B on MRR (mm³/min) when C and D are kept constant at (6A and 145V) At the same time, the remainder parameter is kept at a constant level. The MRR increases when the wire tension (A) increases in the higher current (C). The MRR values have not been affected when reducing the wire tension (A) in the higher current (C) region.



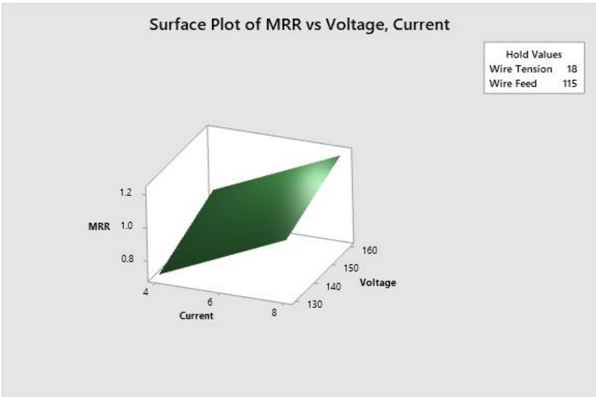
(a)



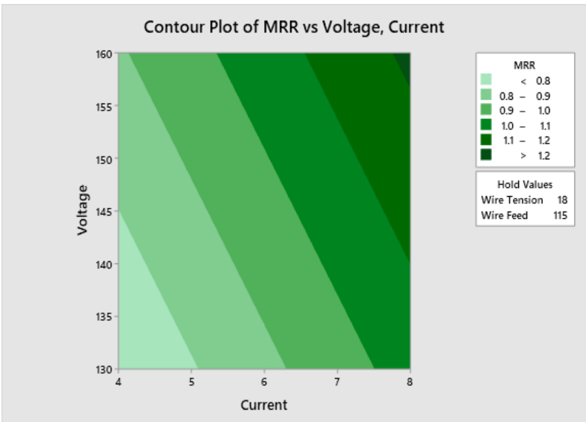
(b)

Figs 7 (a and b): a plots showing combined effects of B and D on MRR (mm³/min) when A and C are kept constant at (18N and 6A)

Figs 8(a & b), shows the combined effects of current (C) and voltage (D) on MRR when wire tension (A) and wire feed (B) are kept 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.



(a)



(b)

Figs 8 (a and b): a plots showing combined effects of C and D on MRR (mm³/min) when A and B are kept constant at (18N and 115 mm/s)

3.4.Optimization plot

The optimization plot shown in Fig 9 represents the influence of each parameter on the response. The developed models were used for optimizing the cutting input parameters. Optimizations were calculated for each model separately without considering the other responses. 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 individual response calculation are presented in Table 9.

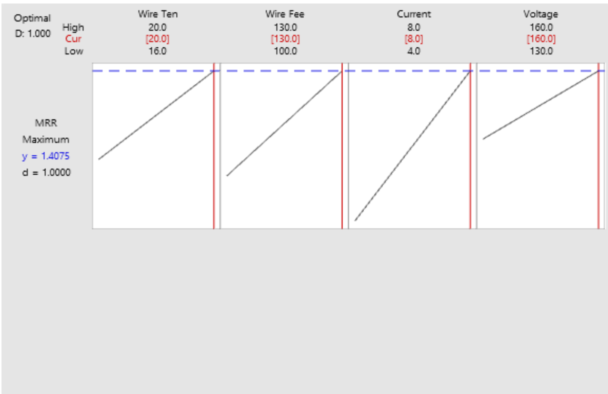


Fig 9: MRR Optimization plot

Table 8: Shows the optimization criteria for input/output cutting parameters

Parameters / Responses	Criteria	Importance
Wire Tension	Range	+++
Wire Feed	Range	+++
Current	Range	+++
Voltage	Range	+++
MRR	Max	+++++

Table 9: Shows the numerical optimization results based on individual response

	Parameters				
Responses	WT	WF	C (A)	V	Response

	(N)	(mm/s)		(V)	
MRR (mm³/min))	20	130	8	160	1.407

4. Conclusions

In the present research work, 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 were presented in the following points:

1. Using a Minitab inspired by the full factorial design approach, achieving the best operating parameter window and developing models to control the cutting parameters is possible.
2. The models achieved using full factorial design or (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, and consequently the MRR increased.
4. The model performed using full factorial design between cutting parameters and MRR of SS-304 stainless steel is acceptable due to the 94.94% of the actual data described by the model.
5. The ANOVA show that the current was the most significant factor.
6. Using the full factorial design method in Minitab software, the optimum parametric setting predicted by the model that given the optimum values of maximum (MRR) obtained under: wire tension = 20N, wire feed = 130mm/s, current = 8A, and voltage= 160V.

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