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Research Article

Optimization on Material Removal Rate and Surface Roughness of Stainless Steel 304 Wire Cut EDM by Response Surface Methodology

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In this work, wire cut electrical discharge machining (WEDM) is used for the material removing processes; it is utilized for machining conductive parts where it is required to produce complicated shapes, new profiles, new geometry, new product development, and high-accuracy components. This machining process is best suitable for high-end applications such as aerospace, automations, automobile, and medical devices. At present, most of the industrial sectors choose the WEDM process because it is used to develop products in a very short development cycle and at a better economic rate. In this paper, the selected complex geometry of the metal sample was eroded away from the wire during the WEDM process, which eliminates mechanical tensions during machining. The effect of different WEDM operation variables set as wire speed, wire tension, discharge current, dielectric flow rate, and pulse on and off time on the parameter, stainless steel 304 material removing rate (MRR) using RSM, has been studied. The MRR will be maximized if the optimum sets of operational variations are used and also achieve a superior surface finish.

1. Introduction

WEDM, also called as "spark," is a machining technique that employs electrical output to obtain a variety of shapes. WEDM is a unique variation of the traditional EDM technique that starts the electrical sparking process using an electrode. The thin continuous brass, copper, or tungsten made wire electrode with a diameter of 0.05-0.3 mm moves constantly, which makes use of that may attain a better tiny corner radius of WEDM. Using a series of rapidly recurring current outputs among the two electrodes separated by a dielectric solution and placed at an electric voltage, the material is removed from the workpiece. The tool-electrode, or simply the "tool" or "electrode," is one of the electrodes, whilst the workpiece-electrode [1, 2], or just the "work-piece", is the other electrode.

As the distance between the electrodes decreases, the intensity of the electric field in the volume between them

exceeds the strength of the [3–5] dielectric (at least at few point(s), that breakup the allowed current to flow among the two electrodes). This is analogous to the breaking of the capacitor. From this, the material is removed from the two electrodes [6].

When the current flow slows (or stops—based on the generator), fresh solution-based dielectric is frequently introduced into the internal-electrode volume, allowing solid elements to be removed and the dielectric's insulating characteristics to be recovered [7]. Flushing is the process of replenishing the interelectrode volume with a new liquid dielectric. Additionally, following a current flow, the potential differentiation among the two electrodes [8] is recovered to its prebreakdown state, allowing for another liquid dielectric breakdown. Wire EDM is used in various manufacturing industrial applications: soft armors shaping, hybrid composite, and mainly in the coating industries (thermal spray processes) for cutting the base materials into the desired shape [9–20].

The mechanism of wire EDM process parameters is most similar to conventional EDM. The conventional EDM process will create an erosion effect on the sample surfaces to remove the material. The basic mechanism involved in the electric discharge machining (EDM) process is that the tool electrode is the cathode and the sample material is the anode. The developed voltage is passed between the two electrodes, and dielectric medium is passed between them to create a strong electrostatic effect. This effect produces a spark gap between the tool and sample. Huge thermal energy is created, and it melts material and vaporizes the material from the sample. The modification of pulse energy and current durations in the dielectric medium can determine the dimensional accuracy and quality of the machining samples [21–25].

To improve the dimensional accuracy and quality of the wire EDM process, it has many working parameters: surface roughness, metal removal rate, wire feed rate, pulse on time, pulse off time, peak current, pulse current, applied voltage, etc.

These all parameters mostly influence the performance of wire EDM machining processes. The proper selection of optimal parameters plays a very important role in the wire EDM machining process; it leads to dimensional accuracy and a quality surface finish. The improper selection of process parameters will lead to dimensional inaccuracy, poor quality, and surface finish; it also leads to wire breakage in the continued machining process; and it affects the performance of the process [26–29].

The most accurate optimization technique is the response surface methodology (RSM) based linear regression model is used in this work. The popularity and simplicity of this technique needed to control various parameters in the wire EDM process. In the present work, surface roughness, MRR, pulse on time, pulse off time, and peak current values are chosen for performance measurement. The selected parameters are the most essential things to get dimensional accuracy and quality finishing in the WEDM process. Many researchers have proved that using the RSM technique is most helpful in carrying out experiments with this technique, which leads to minimal experimental effort [30–33].

2. Experimentation

2.1. 304 Grade Stainless Steel. The most popular stainless steel is SAE 304, commonly known as A2 stainless steel (A2 steel tool not to be confused) with or stainless steel (18/8), standard 1.4301. The major noniron components of steel are chromium (typically 18%) and nickel (usually 8%). Its steel is made of austenite. It is nonmagnetic and not particularly electrically or thermally conductive. It is extensively used because it is easy to mold into different forms and has a better corrosion resistance than ordinary steel. Screws, machinery components, textiles, and other household and industrial items are made of stainless steel 304. These SS 304 grade materials are also used in defense applications like aircraft, armors, and shields as well. But the machining operations performed with this material are very difficult in traditional methods, and there are many proven literature studies available [34–37]. The experiment runs in the WEDM process with various optimized parameter values fed into the machine, and the machined sample design is shown in Figure 1.

2.2. Stainless Steel: Grade 304 (Uns S30400). Standard chemical formula: Fe, <0.08% C, 17.5-20% Cr, 8-11% Ni, <2% Mn, <1% Si, <0.045% P, and <0.03% S. Detailed chemical compositions are shown in Table 1.

2.3. Tool for Machining. The experiment findings were achieved using an Electronica Machine Tools Ltd wire-cut EDM machine (ULTRACUT S2), as shown in Figure 2. The technical specifications of the ULTRACUT S2 WEDM are shown in Table 2.

2.4. Performance Measures. WEDM performance is often assessed using the following criteria, independent of the electrode material and dielectric fluid used.

2.4.1. Material Removal Rate (MRR). Its greatest is a key indicator of the WEDM process' efficiency and cost-effectiveness. However, increasing MRR is not necessarily desired for all applications, since it may compromise the work piece's surface integrity. Fast removal rates result in a rough surface finish.

The expression of material removal rate (MRR) can be obtained from the WEDM. MRR = cutting velocity × wire diameter × material thickness.

2.4.2. Roughness of the Surface (Ra). The WEDM process creates a huge number of craters on the surface, which are created by the discharge energy. The quality of the surface is mostly determined by the amount of energy per spark.

2.5. Parts Programming in Machine. The component programming system receives the profile's geometry and the mobility of the wire electrode cutter along its

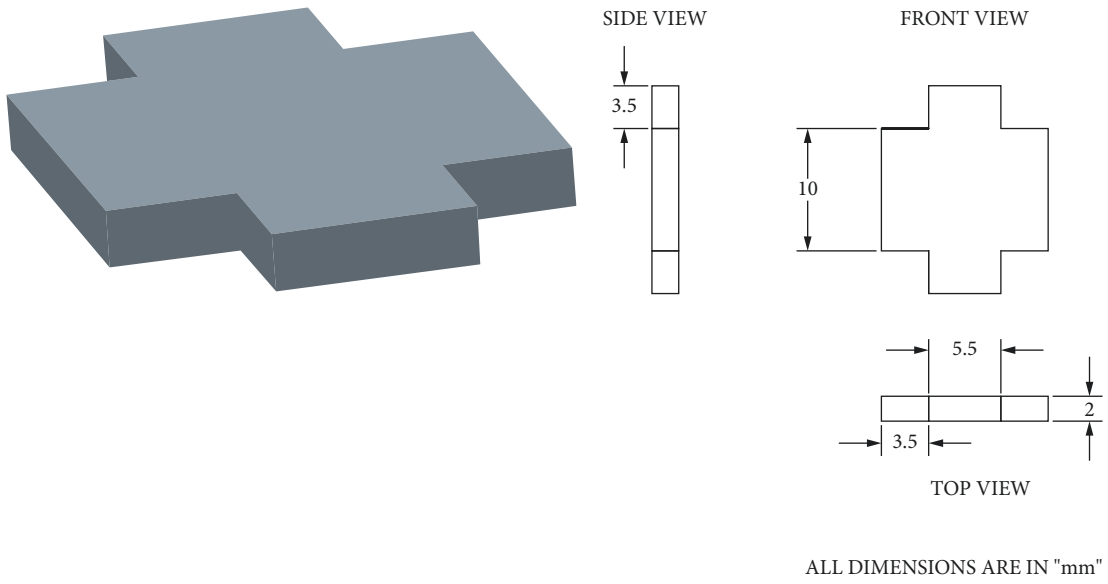

Figure 1: (a) Component 3D model and (b) detail 2D drawing.

Table 1: Chemical composition.

C%	0.017
Si%	0.41
Mn%	1.80
Cr%	18.08
Mo%	0.57
Cu%	0.56
Ni%	8.02
Co%	0.113
P%	0.031
S%	0.026
N%	0.087

Figure 2: Wire-cut EDM machine ULTRACUT S2.

keyboard, in terms of different definitions of points, lines, and circles as tool path elements, in a completely menu-driven, conversational manner. Each path element's wire compensation and taper gradient may be customized

Table 2: Technical specification of the ULTRACUT WEDM.

Model	ULTRACUT S2
Make	Electrica, Pune
Generator	El pulse 50 S
Travel range	
Main table traverse (X, Y)	X 600 mm, Y 400 mm
Auxiliary table traverse (Uv)	U ± 40 mm, V ± 40 mm
Vertical	Z 325 mm
Max. table size	860 × 580 mm
Max. work piece size	1150 × 810 x 300
Max. work piece weight	1000 kg
Feed	
Main table feed rate	900 mm/min
Resolution	0.001 mm
Wire feed rate	0.15 m/min
Max. taper cutting range	±15°/100 mm
Dielectric supply unit	
Dielectric fluid	DM water
Dirty tank	900 ltr
Clean tank	300 ltr
Wire diameter	0.25 mm
Program	El cam V1.14 with hardware
Lock	(USB-3049-2943)

individually. After feeding the profile into the computer, all of the path's numerical information is automatically computed, and a printout is produced. On the visual display panel, the entered profile may be checked. The computer records the successful profile definition, which is subsequently sent into the generator for programmed execution. The machine input data are detailed in Tables 3 and 4.

2.6. Surface Roughness Tester. The surface roughness value for specified experimental components is measured using

Table 3: Input parameters and their levels.

Factor	A	B	C
Input parameter	Pulse ON, (T-ON)	Pulse OFF, (T-OFF)	Peak current(IP)
Units	μs	μs	Amps
Level 1	105	115	125
Level 2	43	53	63
Level 3	170	190	210

Table 4: Response surface methodology design.

Sl. no.	X1 (T –ON)	X2 (T- OFF)	X3 (IP)
1	1	0	0
2	0	1	0
3	0	0	0
4	0	−1	0
5	−1	1	−1
6	0	0	1
7	1	−1	1
8	0	0	−1
9	0	0	0
10	0	0	0
11	0	0	0
12	−1	−1	−1
13	1	1	1
14	−1	0	0
15	1	−1	−1
16	−1	−1	1
17	0	0	0
18	0	0	0
19	1	1	−1
20	0	1	−1

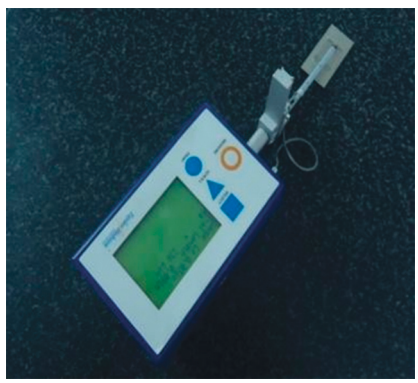

Figure 3: Roughness tester.

Taylor Hobson, Surtronic25 Roughness Testers. The surface roughness tester used is presented in Figure 3 and its specifications are listed in Table 5.

2.7. Material Removal Rate: Calculations. The MRR surface finish has conducted 20 experiments with various parameters like cutting velocity, MRR, and surface roughness. Various machining parameters were selected to perform this work. The obtained Ra value of all these experiments is shown in Table 6.

Table 5: Taylor Hobson.

Model	Surtronic25
Range	00-300 μm
Evaluation length	2.50 mm–25.0 mm
Cutoff	0.25 mm–2.50 mm

Table 6: Result of MRR and surface finish.

Wire diameter (mm)	0.25	Material thickness (mm)	2.052
Sl. no.	Cutting velocity. (mm/min)	MRR (mm^3/min)	Ra,(μm)
1	7.8	3.933	2.711
2	8.2	4.303	2.939
3	8.9	4.557	2.92
4	9.2	4.507	2.802
5	8.6	4.214	2.919
6	9.4	4.474	3.012
7	8	4.325	2.807
8	9.8	4.716	2.946
9	9.6	4.523	2.922
10	8.3	4.572	2.968
11	8.4	4.567	2.926
12	7.6	4.104	2.848
13	7.9	3.807	3.021
14	8.8	4.209	2.784
15	7.4	3.687	2.352
16	9	4.565	2.894
17	9.1	4.557	2.92
18	8.9	4.572	2.938
19	7.8	4.326	2.915
20	7.2	3.736	2.707

$$\begin{aligned}&\text{Material Removal Rate (MPR)}\\&= Vc\ x\ \text{Wire Dia}\ x\ \text{Material Thickness}\\&= 7.8 \times 0.25 \times 2.052.\\&= 3.933^{\circ}\frac{\text{mm}^3}{\text{min}}.\end{aligned} \tag{1}$$

3. Results and Discussions

These experimental results were obtained using a specific WEDM process. The wire diameter is 0.25 mm, the material is brass, and the dielectric fluid is di-ionized water. The experimental design matrix results are displayed in Tables 7–11. The obtained results from experiments are conducted with the specific input process parameters such as pulse on time (T-on),μs; pulse off time (T-off), μs; and peak current(IP), amps, with various levels of experiments shown in Table 7.

From Table 8, it is evaluated that the coefficients of estimated regression for surface roughness are very close to the unity value of (R^2 or R-Sq = 0.9860) and the adjusted coefficient is (R^2 or R-Sq Adj. = 0.9730). This RSM model indicates the estimators of acceptable values with the proper

Table 7: Results obtained from experiment.

Exp. no.	Input process parameter					
	Pulse on time(T-on),μs		Pulse off time (T- off),μs		Peak current(IP), amps	
	Coded	Actual	Coded	Actual	Coded	Actual
1	1	125	0	53	0	190
2	0	115	1	63	0	190
3	0	115	0	53	0	190
4	0	115	−1	43	0	190
5	−1	105	1	63	−1	170
6	0	115	0	53	1	210
7	1	125	−1	43	1	210
8	0	115	0	53	−1	170
9	0	115	0	53	0	190
10	0	115	0	53	0	190
11	0	115	0	53	0	190
12	−1	105	−1	43	−1	170
13	1	125	1	63	1	210
14	−1	105	0	43	0	190
15	1	125	−1	43	−1	170
16	−1	105	−1	43	1	210
17	0	115	0	53	0	190
18	0	115	0	53	0	190
19	1	125	1	63	−1	170
20	−1	105	1	63	1	210

Table 8: Coefficients of estimated regression for surface roughness, Ra.

Term	Coef	SE coef	T	*P*
Constant	0.682524	2.10589	0.324	0.753
A	0.201951	0.03963	5.096	0.000
B	−0.00411	0.02071	−0.198	0.847
C	−0.099919	0.01431	−6.982	0.000
A ∗ A	−0.001524	0.00017	−9.011	0.000
B ∗ B	−0.000403	0.00016	−2.553	0.029
C ∗ C	0.000184	0.00003	5.286	0.000
A ∗ B	0.001104	0.00008	13.35	0.000
A ∗ C	0.000455	0.00004	10.638	0.000
B ∗ C	−0.00379	0.00004	−8.86	0.000
S	R-Sq		R-Sq (Adj)	
0.02419	98.60%		97.30%	

Table 9: Variance analysis for surface roughness, Ra.

Source	DF	Seq-SS	Adj-SS	Adj-MS	F	*P*
Regression	9	0.413512	0.413512	0.04592	78.52	0.000
Linear	3	0.109886	0.03622	0.012134	20.63	0.000
Square	3	0.087207	0.10881	0.036395	61.99	0.000
Interactions	3	0.21642	0.21642	0.072064	123.29	0.000
Residual error	10	0.005851	0.005851	0.000573	-	-
Lack of fit	5	0.004096	0.004096	0.000807	2.33	0.187
Pure error	5	0.001755	0.001755	0.00034	-	-
Total	19	0.419363	-	-	-	-

Table 10: Coefficients of estimated regression for material removal rate (MRR).

Term	Coef	SE coef	T	*P*
Constant	−53.3003	6.42397	−8.297	0.000
A	0.986	0.1209	8.155	0.000
B	0.2197	0.06317	3.477	0.006
C	−0.0424	0.04366	−0.971	0.354
A ∗ A	−0.0046	0.00052	−8.963	0.000
B ∗ B	−0.0009	0.00048	−1.901	0.087
C ∗ C	0.0003	0.00011	2.509	0.031
A ∗ B	0.001	0.00025	4.082	0.002
A ∗ C	0.0001	0.00013	0.652	0.529
B ∗ C	−0.0013	0.00013	−10.043	0.000
S	R-Sq		R-Sq(Adj)	
0.07379	97.00%		94.40%	

Table 11: Variance analysis of material removal rate (MRR).

Source	DF	Seq SS	Adj SS	Adj MS	F	*P*
Regression	9	1.78682	1.78682	0.198536	36.46	0.000
Linear	3	0.09402	0.76464	0.254879	46.81	0.000
Square	3	1.0506	1.09863	0.366211	67.26	0.000
Interactions	3	0.6422	0.6422	0.214067	39.32	0.000
Residual error	10	0.05445	0.05445	0.005445	-	-
Lack of fit	5	0.05275	0.05275	0.010549	31.03	0.001
Pure error	5	0.0017	0.0017	0.00034	-	-
Total	19	1.84127	-	-	-	-

degree of freedom and ideal architecture for reactive extraction process predictive simulations shown in Table 8. The ANOVA predicted results shown in Tables 9–11 give a T-value of 0.324, −8.297; *P*-value of 0.753; and an F-value of 78.52, 36.46 in the RSM model outlined as significant.

The significance to look at the obtained values in the model is that they correspond to peak current, pulse on time, and pulse off time. The surface roughness values are controlled with pulse on time and pulse off-time set input mean values shown in Tables 8 and 9. The material removal rate will be controlled with peak current modifications shown in Tables 10 and 11. The optimized output responses are shown in Figures 4 to 8.

3.1. Regression Analysis for Material Removal Rate. The findings of the experiments were used to create a mathematical model that expressed the connection between process parameters and MRR. Multiple regressions are used to calculate the coefficients of mathematical models, as shown in Figure 4.

$$\begin{aligned} \text{MRR} = {} & -53.3033 + 0.986 \times \text{Ton} + 0.2197 \times \text{Toff} \\ & - 0.042 \times \text{IP} - 0.0046 \times \text{Ton}^2 - 0.0009 \times \text{Toff}^2 \\ & + 0.0003 \times \text{IP}^2 + 0.001 \times \text{Ton}\, x\, \text{Toff} + 0.0001 \\ & \times \text{Ton}\, x\, \text{IP} - 0.0013 \times \text{Toff}\, x\, \text{IP}. \end{aligned} \quad (2)$$

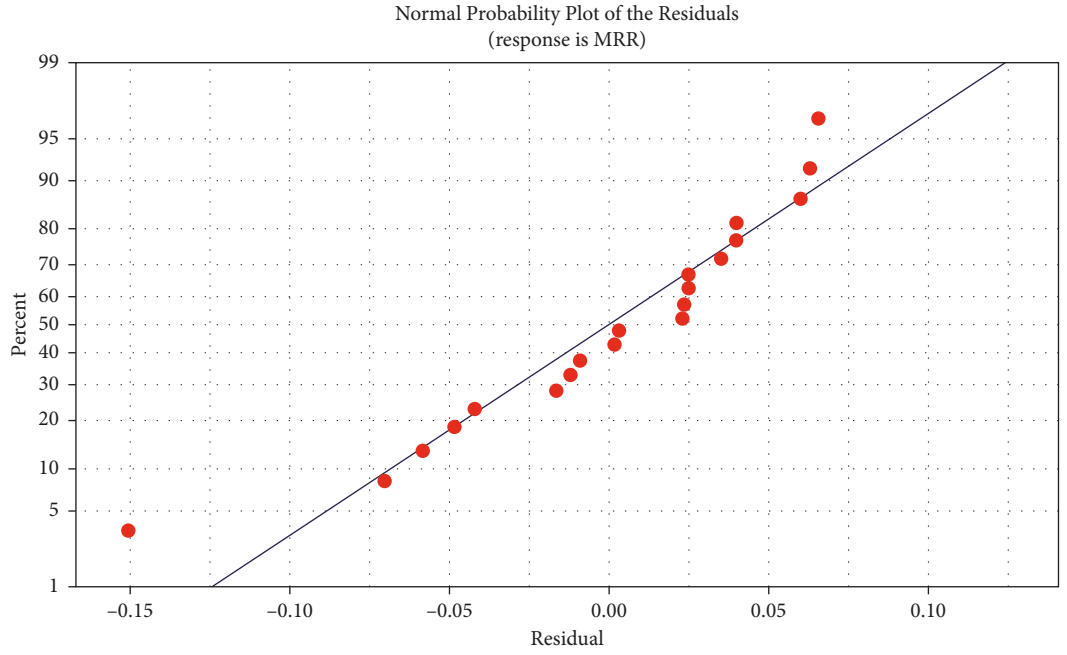

Figure 4: Normal probability plot of the residuals of the MRR.

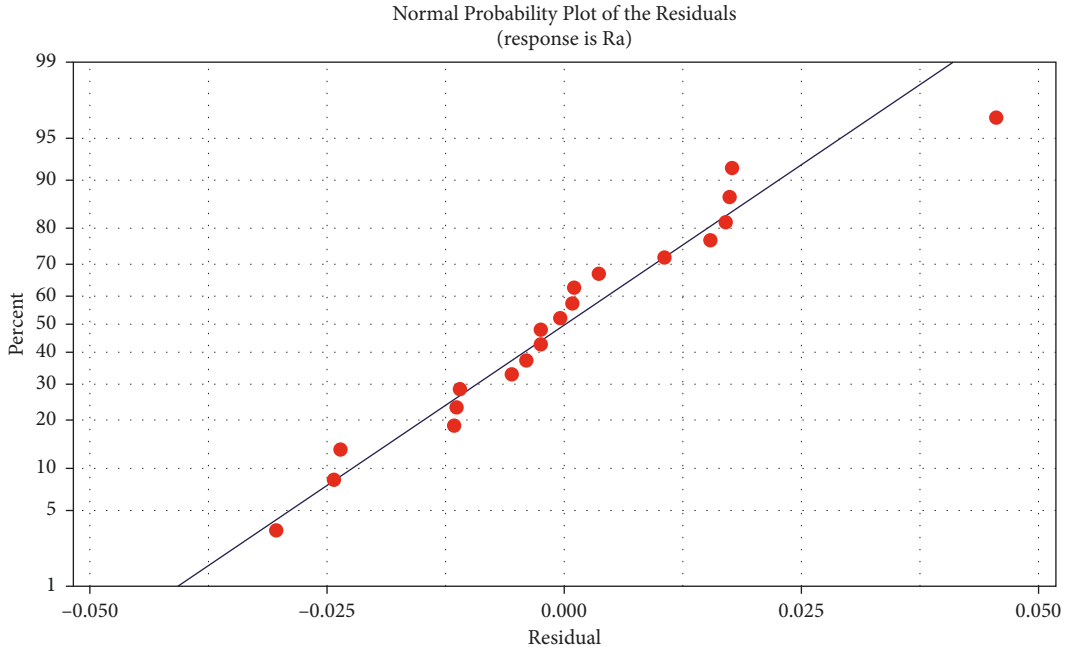

Figure 5: Normal probability plot of the residuals of surface roughness. The wire EDM process completed the given input process parameter. Shapes of component profile are shown in Figure 6.

3.2. Regression Analysis for Surface Roughness. The findings of the experiments were utilized to create a mathematical model that expressed the connection between process parameters and surface roughness, as shown in Figure 5. Multiple regressions are used to calculate the coefficients of mathematical models.

$$SR = 0.682524 + 0.201951\,x\,\text{Ton} - 0.\,00411\,x\,\text{Toff} - 0.099919\,x\,IP - 0.001524\,x\,\text{Ton}^2 0.000403\,x\,\text{Toff}^2 + 0.000184\,x\,IP^2 + 0.001104\,x\,\text{Ton}\,x\,\text{Toff} + 0.0004551\,x\,\text{Ton}\,x\,IP - 0.000379\,x\,\text{Toff}\,x\,IP. \quad (3)$$

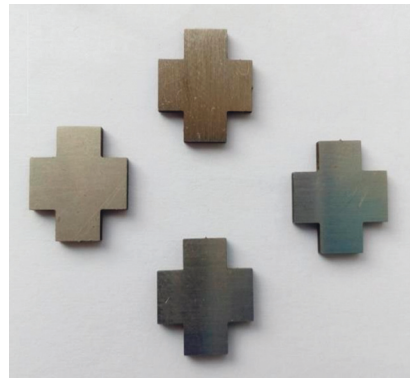

Figure 6: Wire EDM component profile.

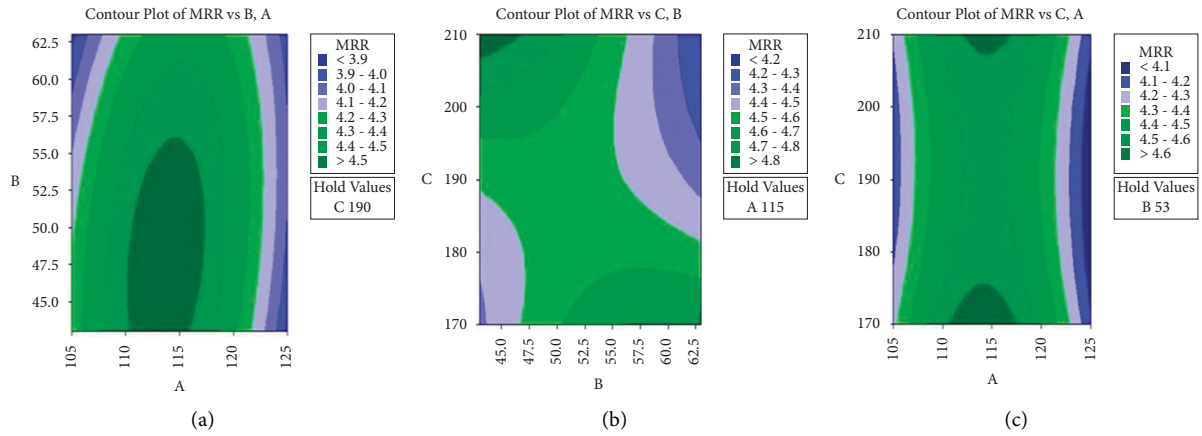

Figure 7: (a) Contour plot Of MRR vs (B) A., (b) contour plot of MRR vs (C) B., and (c) contour plot Of MRR vs C, A.

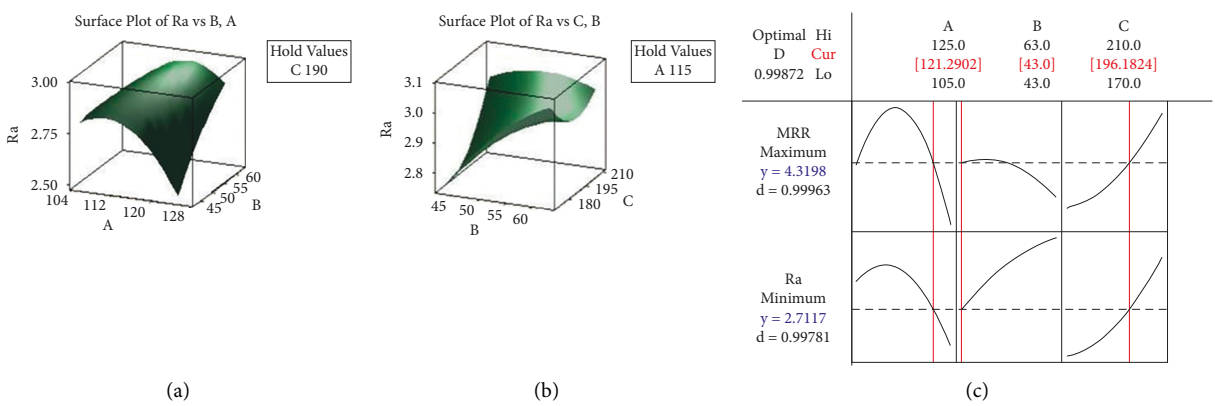

Figure 8: (a) Surface plot of Ra vs (C) A., (b) surface plot of Ra vs (C) B., and (c) optimization plot of MRR, Ra.

The response optimization plot for MRR and Ra is shown in Figures 7 and 8. The ultimate goal of our research is to increase MRR while reducing surface roughness.

Figure 7 shows the 2D contour response surface of MRR, and Figure 8 shows the 3D response surface of Ra. The MRR values vary with the changes in the discharge voltage and peak current. The Ra value leads to an electrode spark energy gap between the tool and the sample material. There are many combinations selected with MRR and Ra parameters, to opt with the graphs. This graph shows the increasing MRR value has a tendency to decrease surface roughness (Ra) [38–42].

In order to evaluate whether the maximum value of MRR and Ra is minimum, the desirability method was utilized to determine the optimal value of variables (Ra). The greatest values of MRR = 4.3198 and Ra = 2.7117 are achieved for the following combination of variables, as shown in the graph [43–45].

$$T\,\text{On} = 121.2902\,(\mu s),$$
$$T\,\text{Off} = 43\,(\mu s), \quad (4)$$
$$IP = 196.182\,(\text{amp}).$$

4. Conclusion

(i) As a consequence, the tests were performed on a WEDM machine, and the experimental research findings were derived from the work completed.

(ii) The pulse on time increases with respect to the surface roughness.

(iii) To achieve a superior surface finish for the specified test range in a 304 stainless steel material, utilize a high pulse on time of 121.2902 (s), a low pulse off time of 43.00 (s), and a peak current of 196.182 (amps) in the WEDM Process. The surface roughness optimal value is 2.7117, while the material removal rate is 4.3198.

(iv) The stainless steel 304 material has better corrosion resistance, high strength in mechanical properties, and is best suited for many chemical industries, automobiles, and customized machine spare manufacturing applications. The hardened stainless steel 304 work materials during re-machining is a major problem in mechanical industries. The wire-cut electric discharge machining process will solve that problem easily.

Data Availability

The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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