engineering proceedings

MDPI

Proceeding Paper

Modelling and Optimization of Surface Roughness and Material Removal Rate in Wire Electrical Discharge Machining of Nimonic 90 †

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† Presented at the 4th International Conference on Advanced Manufacturing and Materials Processing (AdvaMAP 2026), Porto, Portugal, 19 July 2026.

Abstract

Optimal process conditions are key for obtaining the desired machinability in machining processes. This study uses an optimization approach for wire electrical discharge machining (WEDM) of Nimonic 90. Surface roughness and material removal rate (MRR) are considered as process responses. WEDM experiments were conducted under different levels of process inputs. Response surface methodology (RSM) and the desirability function approach were used to model the process inputs and outputs. The optimal machining conditions were a servo voltage of 30 V, wire tension of 4 N, wire feed rate of 3 mm/min, pulse on time of 7.97 µs, and pulse off time of 38.48 µs, resulting in an overall desirability of 0.68. The developed models were validated through confirmation tests. The models showed good agreement with the experimental results, with correlation coefficients of 0.97 for surface roughness and 0.99 for MRR. The proposed approach provides a useful tool for WEDM process modelling and optimization.

Keywords: Nimonic 90; WEDM; surface roughness; material removal rate; multi-objective optimization; RSM

1. Introduction

Nickel-based alloys are mostly used in the aerospace industry because of their high strength and good resistance to fatigue and corrosion at high temperatures. They are commonly used in the manufacture of turbine blades, hot-working tools, discs, forgings, and ring sections [1]. However, their high hardness and abrasive nature make them difficult to cut using regular methods. These challenges often lead to high cutting forces, shortened tool life, and poor surface quality. Under these conditions, WEDM is suitable for difficult-to-machine components. WEDM removes material through controlled electrical discharges and provides good dimensional precision and surface quality. The machinability of WEDM depends greatly on the selection of process parameters. These are as follows: (i) discharge parameters (pulse on time, pulse off time, peak current, and servo voltage); (ii) wire electrode characteristics (wire material, diameter, coating, tension, and feed rate); and (iii) dielectric conditions (dielectric conductivity and flow rate) [2,3]. These parameters have a substantial influence on machinability performance.

Process modelling is useful in assessing product quality, improving productivity, and optimizing process efficiency by establishing relationships between input parameters and

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Academic Editors: Ch Sateesh Kumar, Himadri Majumder, Abhishek Sharma and Filipe Fernandes

Published: 13 November 2026

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outputs. Statistical methods can accelerate process modelling and the selection of optimal machining conditions. Many researchers have used statistical and optimization methods for WEDM of nickel-based alloys. Amitesh Goswami and Jatinder Kumar [4] successfully applied GRA and the Taguchi to model input conditions and surface roughness, MRR, and wire wear ratio during WEDM of Nimonic 80A alloy. Ramakrishnan R. and Karunamoorthy L. [5] showed that a multi-response optimization could successfully model and predict machinability of Inconel 718. In another study [6], genetic algorithm-based optimization was used in WEDM of Nimonic 90 to optimize process parameters and identify the dominant factor affecting surface roughness. M.L. Kulkarni and Sachin Ashok Sonawane [7] conducted WEDM experiments on Nimonic 75 to model process conditions for surface roughness and MRR. Singh et al. [8] used RSM to study WEDM of Nimonic 80A and optimize the process parameters for MRR and kerf width. Similarly, another study [9] used RSM along with a desirability function method to model and optimize process conditions for MRR and kerf width while machining Nimonic 75. Also, a Taguchi-based GRA method was used to optimize MRR, electrode wear, and surface finish in WEDM of Nimonic 75 [10]. These studies reveal that WEDM is a cost-effective and efficient machining method for a wide range of nickel-based alloys. They also show that RSM and other statistical methods can be used for parametric modelling and process optimization.

Previous studies show that RSM has been successfully used to model and optimize the WEDM process of nickel-based alloys. Still, studies using RSM and the desirability function approach for multi-objective optimization of WEDM of Nimonic 90 alloy are relatively scarce. Hence, this study uses an optimization method to model and optimize surface roughness and MRR during WEDM of Nimonic 90. Analysis of Variance (ANOVA) is used to identify the most important input parameters affecting surface roughness and MRR. The desirability function technique is used to evaluate the effectiveness of the RSM model in optimizing process conditions.

2. Materials and Methods

In this work, WEDM experiments were performed using an EX 400 wire-cutting machine (EXCETEK Technologies Co., Ltd., Taichung, Taiwan). Deionized water was used as the dielectric fluid, and a brass wire with a diameter of 0.25 mm was used as the wire electrode. The dielectric fluid temperature was maintained at a constant 27 °C throughout the experiments. Figure 1 shows the WEDM experimental setup and the machined specimens. A Nimonic 90 alloy workpiece with a size of 200 mm × 100 mm × 10 mm was used in the experiments. Surface roughness was tested at three locations on each piece, and the average value was recorded. Figure 2 shows the microstructure of the Nimonic 90 alloy, characterized by gamma prime (γ') phase particles dispersed within a gamma (γ) phase matrix. The chemical composition (Table 1) of the Nimonic 90 alloy was verified through analysis conducted at Jyothi Spectro Analysis, India. Based on the microstructure and chemical composition, it is confirmed that the supplied test material meets the standard specifications of Nimonic 90.

Table 1. Composition of work material (wt.%).

Element	Ni	Cr	Co	Ti	Al	Fe	Si	C	Mn	S
Composition	57.63	19.53	17.89	2.61	1.58	0.09	0.05	0.01	0.005	0.004

https://doi.org/10.3390/engproc2026165006

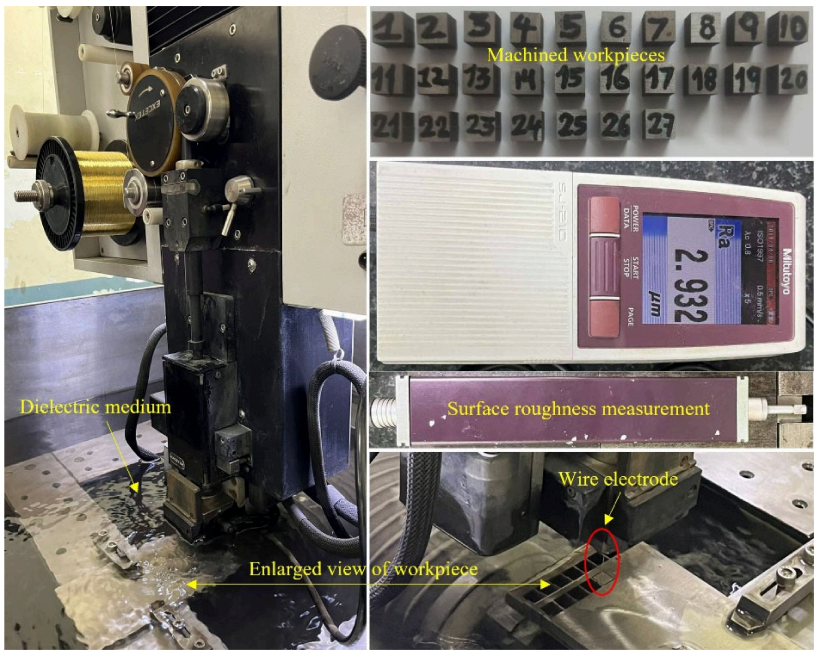


Figure 1. WEDM experimental setup and surface roughness tester.

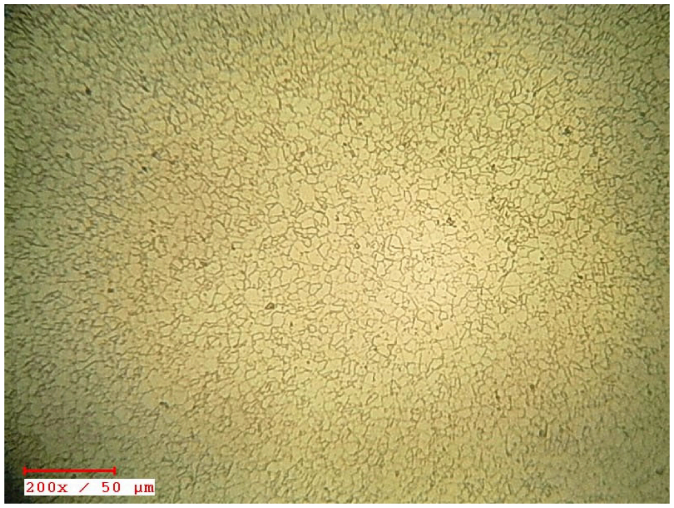


Figure 2. Nimonic 90 microstructure.

Surface roughness is an important machining characteristic that greatly influences the functionality and service life of machine elements. In WEDM, the roughness of machined elements is affected by machining parameters. MRR is another critical parameter for evaluating machinability, as it reflects the efficiency and speed of the process. Therefore, pulse on time, pulse off time, servo voltage, wire tension, and wire feed rate were selected as the machining parameters in this work. The machinability of Nimonic 90 is estimated in terms of surface roughness and MRR under different process conditions. The WEDM experiments were designed using the Taguchi method. The process conditions and experimentally measured responses are provided in Table 2. The quadratic regression equation used in the RSM model is presented in Equation (1).

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \quad (1)$$

where y refers to response, x_i, x_j refers to inputs, β_o is the constant, β_i is the linear term, β_{ii} is the quadratic coefficients, β_{ij} are the interactions, k is the number of inputs, and ϵ refers to error.

Table 2. Experimentally measured surface roughness and MRR.

Exp. No.	Pulse on Time, A (µs)	Pulse off Time, B (µs)	Servo Voltage, C (V)	Wire Tension, D (N)	Wire Feed Rate, E (mm/min)	Surface Roughness (µm)	MRR (mm^3/min)
1	5	35	30	4	9	2.16	4.69
2	15	35	30	4	3	2.96	12.14
3	5	45	30	4	3	2.11	4.44
4	15	45	30	4	9	3.14	10.05
5	5	35	50	4	3	2.30	2.38
6	15	35	50	4	9	3.09	6.80
7	5	45	50	4	9	2.26	1.74
8	15	45	50	4	3	3.04	6.28
9	5	35	30	12	3	2.10	5.64
10	15	35	30	12	9	3.06	11.68
11	5	45	30	12	9	2.19	4.30
12	15	45	30	12	3	2.96	10.27
13	5	35	50	12	9	2.12	2.01
14	15	35	50	12	3	3.04	6.79
15	5	45	50	12	3	2.05	1.49
16	15	45	50	12	9	3.01	6.58
17	5	40	40	8	6	2.08	3.21
18	15	40	40	8	6	3.06	8.50
19	10	35	40	8	6	2.80	6.71
20	10	45	40	8	6	2.75	5.72
21	10	40	30	8	6	2.62	7.94
22	10	40	50	8	6	2.70	5.61
23	10	40	40	4	6	2.47	6.50
24	10	40	40	12	6	2.58	6.36
25	10	40	40	8	3	2.61	6.66
26	10	40	40	8	9	2.45	6.39
27	10	40	40	8	6	2.76	6.15

3. Results and Discussion

3.1. RSM Modelling

RSM is a widely used statistical technique for modelling the relationship between input and output variables. This approach simplifies complex problems by utilizing experimental data, applying mathematical modelling strategies, and eliminating undesired factors. In this work, RSM is employed to model and optimize the WEDM process for Nimonic 90. The regression equations (Equations (2) and (3)) show how the input parameters affect surface roughness and MRR. Figure 3 presents correlation grids showing the correlations between the process parameters and response variables. Pulse on time shows the strongest correlation with surface roughness and MRR, while the other parameters show relatively lower correlations. As shown in Figure 4, the correlation coefficients of 0.97 for surface roughness and 0.99 for MRR indicate a strong agreement between the RSM-predicted and experimental results. Therefore, the RSM model provides an accurate tool for relating WEDM input parameters to the corresponding output responses.

$$\begin{aligned} Ra = {} & 2.69 + 0.4444 * A - 0.0067 * B + 0.0162 * C - 0.0243 * D + 0.0170 * E \\ & + 0.0035 * AB - 0.0069 * AC + 0.0121 * AD + 0.0073 * AE + 0.0194 * BC \\ & - 0.0100 * BD + 0.0257 * BE - 0.0262 * CD - 0.0242 * CE - 0.0011 * DE \\ & - 0.0634 * A^2 + 0.1479 * B^2 + 0.0285 * C^2 - 0.1021 * D^2 - 0.1049 * E^2 \end{aligned} \quad (2)$$

$$\begin{aligned} MRR = {} & 6.30 + 2.73 * A - 0.4417 * B - 1.75 * C + 0.0054D - 0.1041 * E \\ & - 0.0939 * AB - 0.3886 * AC - 0.0091 * AD + 0.0535 * AE + 0.1995 * BC \\ & + 0.0017 * BD + 0.1221 * BE - 0.0573 * CD + 0.1219 * CE + 0.1459 * DE \\ & - 0.5483 * A^2 - 0.1863 * B^2 + 0.3827 * C^2 + 0.0297 * D^2 + 0.1232 * E^2 \end{aligned} \quad (3)$$

where A, B, C, D, and E denote the values of pulse on time, pulse off time, servo voltage, wire tension, and wire feed rate, respectively.

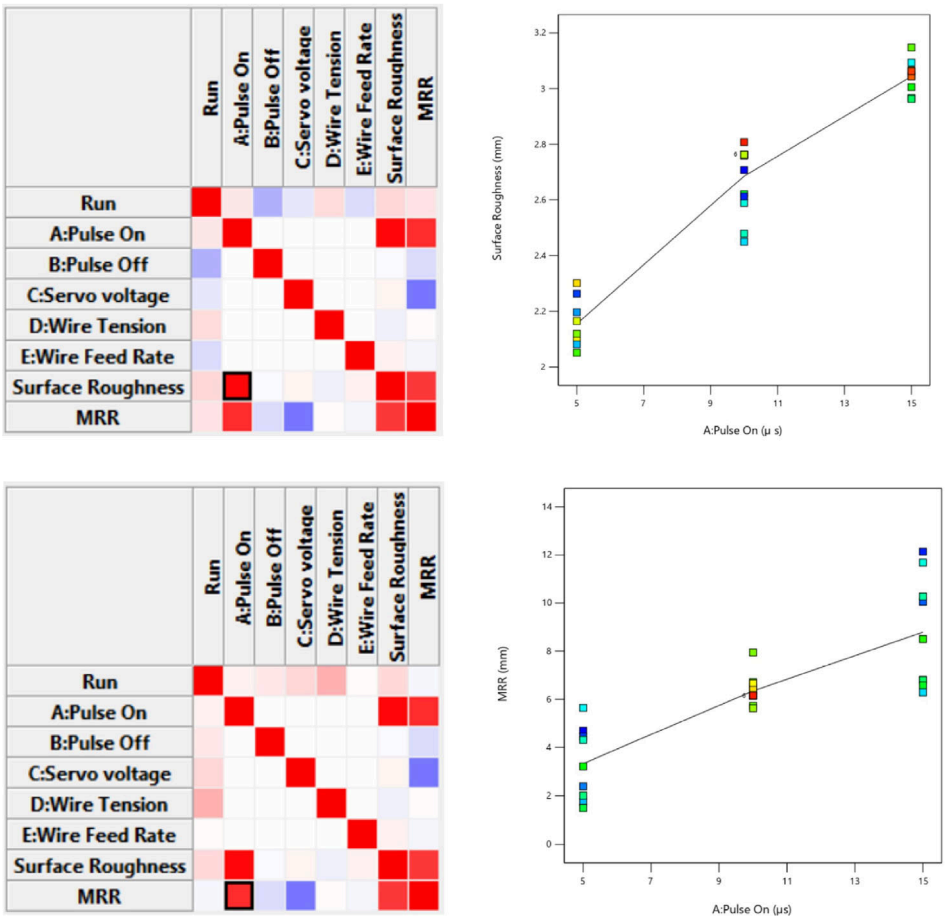


Figure 3. Correlation grid plots.

3.2. ANOVA

ANOVA is used to find the factors that considerably affect process performance. Table 3 presents the ANOVA results for surface roughness. The results indicate that pulse on time is the highest influencing parameter, contributing 91.73% to surface roughness, whereas pulse off time has the least impact, contributing only 0.02%. Servo voltage, wire tension, and wire feed rate contributed only 0.12%, 0.27%, and 0.13%, respectively, indicating their negligible impact on surface roughness. Table 4 shows the ANOVA results for MRR. Pulse on time is the most important parameter, contributing 67.37% to MRR. The contributions of pulse off time, servo voltage, and wire feed rate were 1.76%, 27.56%, and 0.09%, respectively, showing lower impact on MRR. On the other hand, wire tension had the least influence (0.0025%).

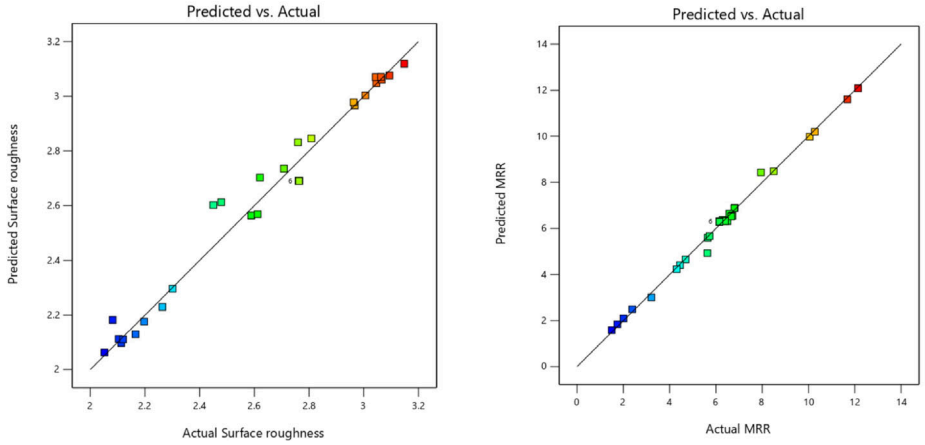


Figure 4. Predicted vs. actual values.

Table 3. ANOVA for surface roughness.

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	*p*-Value	Percentage Contribution
Model	3.58	5	0.7152	62.84	<0.0001	92.50
A	3.55	1	3.55	312.32	<0.0001	91.73
B	0.0008	1	0.0008	0.0715	0.7913	0.02
C	0.0047	1	0.0047	0.4136	0.5258	0.12
D	0.0106	1	0.0106	0.9347	0.3425	0.27
E	0.0052	1	0.0052	0.4588	0.5041	0.13
Residual	0.2959	26	0.0114			7.64
Cor Total	3.87	31				100

Table 4. ANOVA for MRR.

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	*p*-Value	Percentage Contribution
Model	193.06	5	38.61	157.51	<0.0001	96.8
A	134.37	1	134.37	548.14	<0.0001	67.37
B	3.51	1	3.51	14.32	0.0008	1.76
C	54.98	1	54.98	224.29	<0.0001	27.56
D	0.0005	1	0.0005	0.0022	0.9631	0.0025
E	0.1949	1	0.1949	0.7950	0.3808	0.0977
Residual	6.37	26	0.2451			3.19
Cor Total	199.43	31				100

3.3. Effect of Machining Parameters

Surface roughness is important in determining the serviceability of a material, as it directly affects properties such as adhesion and surface texture. Increasing surface quality is often essential for improving product performance. Figure 5 shows the effects of the process inputs on responses during WEDM of Nimonic 90. As shown in Figure 5, an increase in pulse on time leads to an increase in surface roughness. The effects of pulse off time, servo voltage, wire feed rate, and wire tension are comparatively minimal. Another important machinability characteristic is MRR, as it directly affects process efficiency and productivity. Unusual MRR values can result in poor surface quality or even damage to the material. Therefore, understanding the effect of machining parameters on MRR is essential for improving performance. Figure 6 shows the correlation between input parameters and MRR. An increase in pulse on time leads to a corresponding rise in MRR, while wire tension has a relatively smaller impact than wire feed rate. These trends are consistent with results available in previous studies [11].

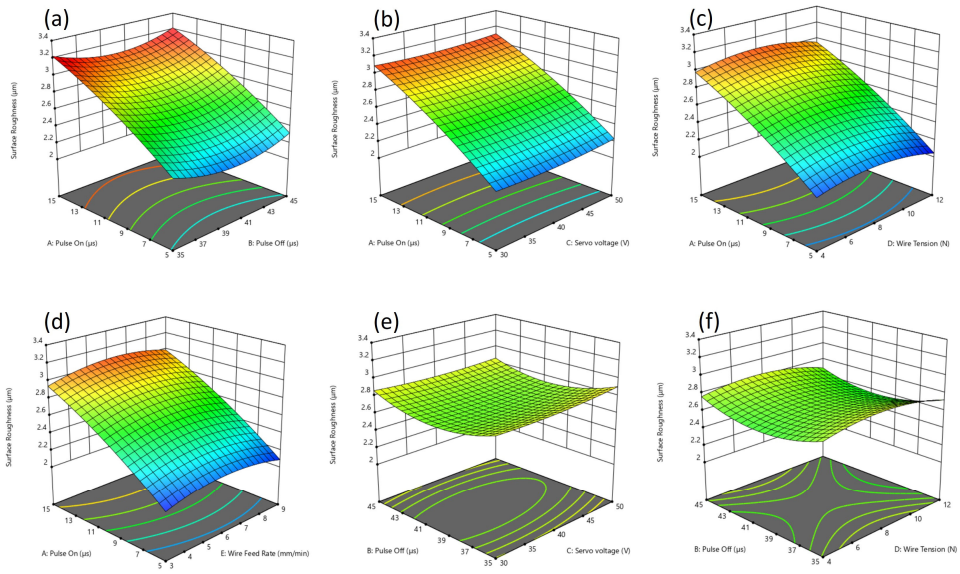


Figure 5. 3D plots showing the effects of different combinations of machining parameters on surface roughness: (**a**) Pulse-on time and pulse-off time; (**b**) Pulse-on time and servo voltage; (**c**) Pulse-on time and wire tension; (**d**) Pulse-on time and wire feed rate; (**e**) Pulse-off time and servo voltage; and (**f**) Pulse-off time and wire tension.

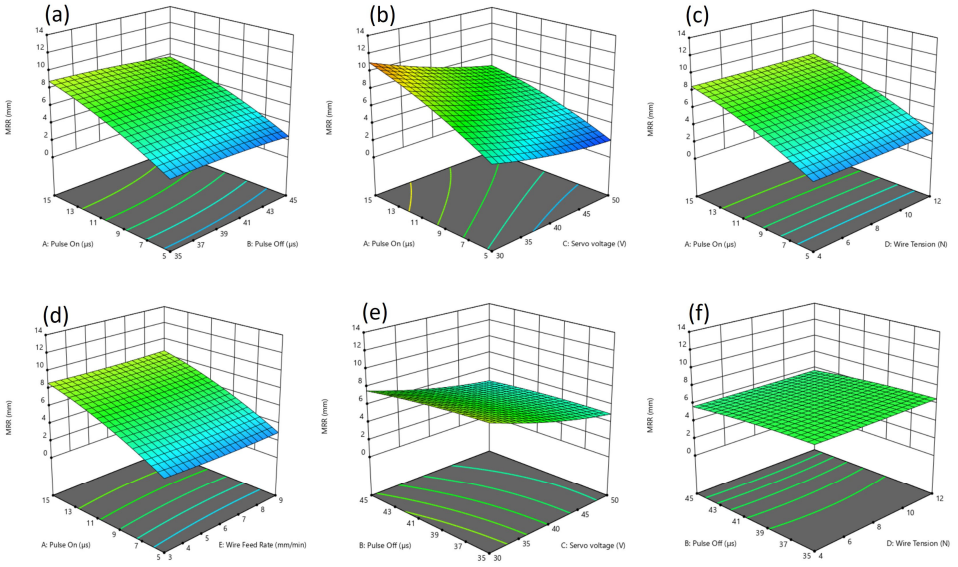


Figure 6. 3D plots showing the effects of different combinations of machining parameters on material removal rate: (**a**) Pulse-on time and pulse-off time; (**b**) Pulse-on time and servo voltage; (**c**) Pulse-on time and wire tension; (**d**) Pulse-on time and wire feed rate; (**e**) Pulse-off time and servo voltage; and (**f**) Pulse-off time and wire tension.

3.4. Multi-Objective Optimization

Surface finish and MRR greatly depend on the selection of appropriate machining conditions. To achieve this, the desirability function approach was used. This approach finds the best solution under the particular constraints. The levels of input parameters were selected as per the industrial practice conditions to minimize surface roughness and maximize MRR. The constraints in Table 5 define the desired parameter settings based on the experimental results. A total of 100 solutions were obtained, with solution 1 identified as the optimal configuration. The optimal machining settings are as follows—pulse on time: 7.97 µs, pulse off time: 38.48 µs, servo voltage: 30 V, wire tension: 4 N, and wire feed

rate: 3 mm/min. Although many solutions may have similar desirability values, the best solution was selected based on the minimum surface roughness and the maximum MRR values. The individual desirability values for surface roughness and MRR were 0.79 and 0.58, respectively. The overall desirability score was 0.68. Figure 7 shows the desirability bar graph with the optimal solution. The first five bars represent the input parameters, whereas the last two represent the optimal responses.

Numerical optimization graphs provide further information into the optimal solution. Figure 8 shows the optimization results as ramp plots, where each ramp represents an input parameter or a response variable. The red dots indicate the optimal values of the input parameters, whereas the blue dots represent the predicted response values. Each response ramp shows whether the response should be minimized or maximized. The ramp plots predict a surface roughness of 2.28 μm and an MRR of 7.75 mm^3/min, with an overall desirability of 0.682, indicating a fair compromise between surface quality and productivity.

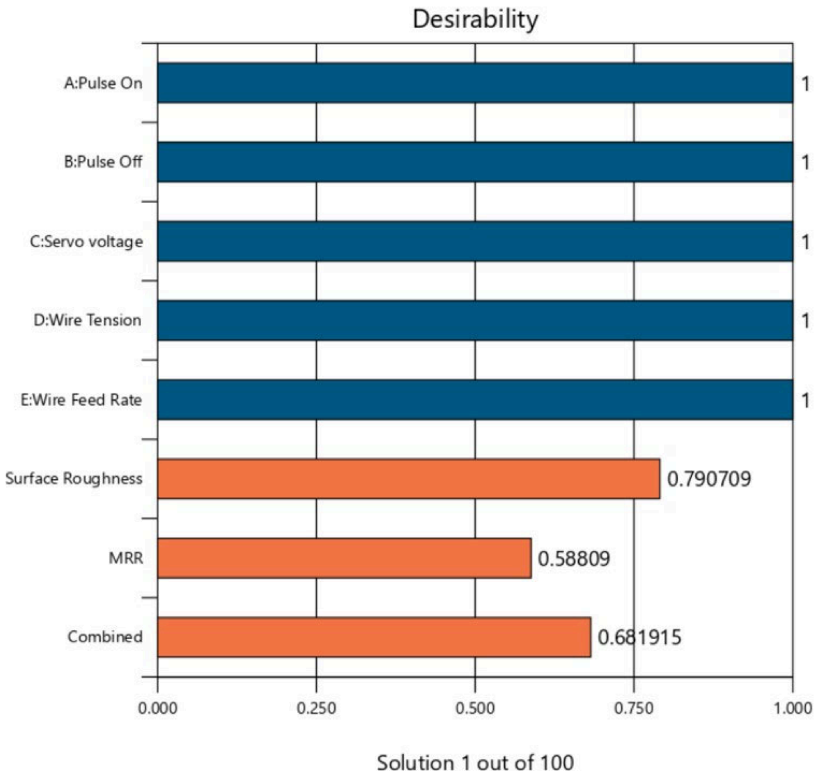


Figure 7. Desirability graph.

Table 5. Constraints and limitations used in the optimization.

Name	Objective	Minimum	Maximum	Lower Weight	Upper Weight	Importance
A	in range	5	15	1	1	3
B	in range	35	45	1	1	3
C	in range	30	50	1	1	3
D	in range	4	12	1	1	3
E	in range	3	9	1	1	3
Surface roughness	none	2.052	3.148	1	1	3
MRR	none	1.498	12.14	1	1	3

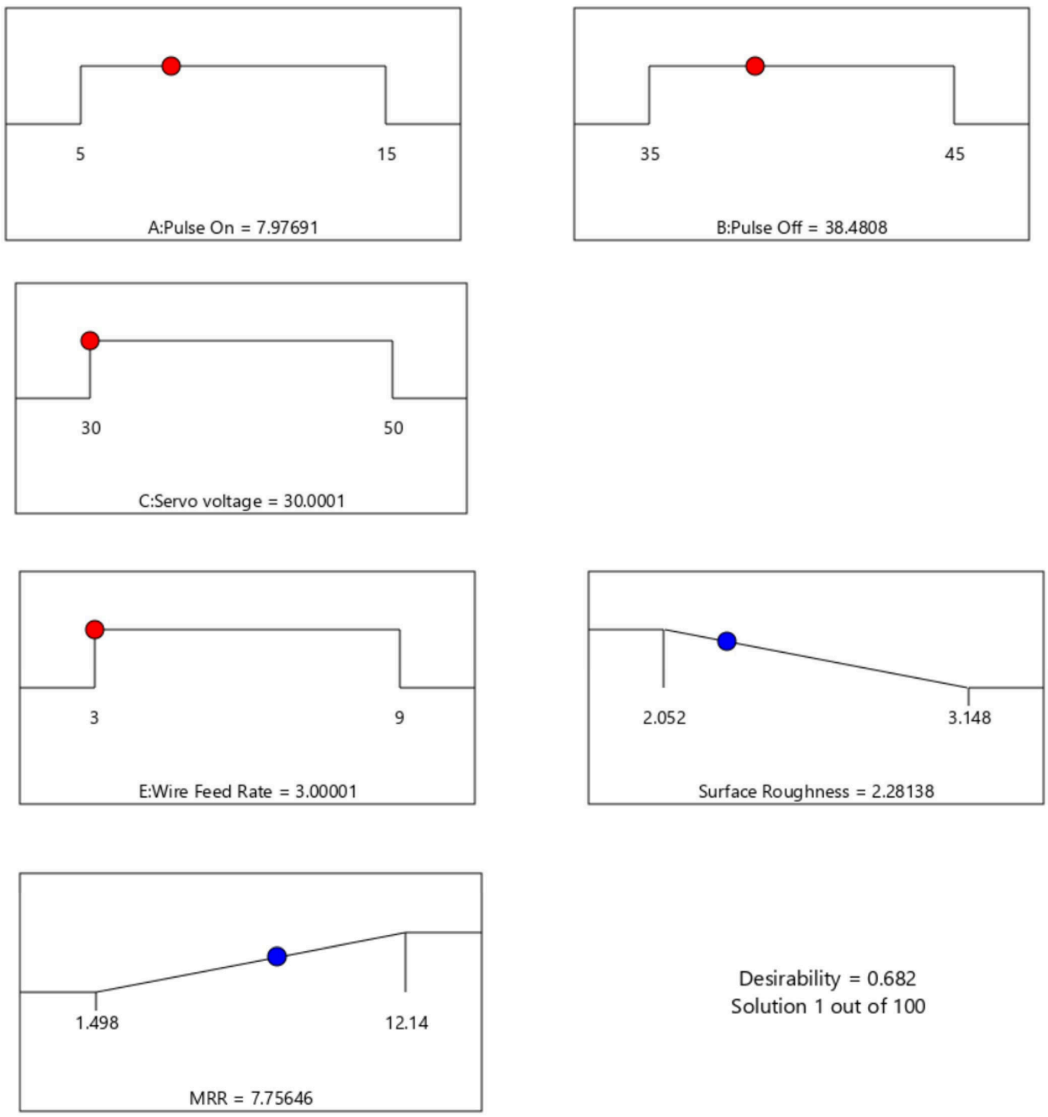


Figure 8. Ramp function for desirability.

3.5. Confirmation Tests

In this study, two methods were used to validate the model: the Anderson–Darling test and experimental confirmation tests. Also, ANOVA was used to determine the impact and effectiveness of the regression model. The Anderson–Darling test was conducted to assess model adequacy. The results showed that 95% of the data points fall within the prediction interval. This test was performed using seven new tests with different combinations of inputs. Figure 9 presents the normal probability plots for surface roughness and MRR, along with the Anderson–Darling test results. The predictions closely follow a normal distribution, proving the assumption of normality. Also, at a significance level of 0.05 (95% confidence), the P-value obtained is reasonably high, indicating that the null hypothesis cannot be denied. These results emphasize the statistical model validity and strength of the regression. In addition, confirmation tests were conducted to validate the accuracy of the model predictions. The optimal machining parameters—pulse on time: 7.97 µs, pulse off time: 38.48 µs, servo voltage: 30 V, wire feed rate: 3 mm/min, and wire tension: 4 N—were used in a new set of experiments. The experimental results obtained under these conditions were compared with the model predictions. The comparison showed prediction errors of 5.6% for surface roughness and 8.4% for MRR, indicating good agreement between the predicted and experimental data. This confirms that the RSM model is

both accurate and reliable in obtaining the correlation between the inputs and outputs in the WEDM of Nimonic 90. Overall, both statistical and experimental validations confirm the applicability of the RSM model for predicting and optimizing surface roughness and MRR. The optimized machining parameters and the predicted responses for the selected solutions are presented in Table 6.

Table 6. Optimized solutions.

S.no	Pulse on	Pulse off	Servo Voltage	Wire Tension	Wire Feed Rate	Surface Roughness	MRR	Desirability	
1	7.977	38.481	30.000	4.000	3.000	2.281	7.756	0.682	Selected
2	8.087	38.141	30.000	4.027	3.000	2.300	7.875	0.681	
3	8.065	38.676	30.011	4.000	3.053	2.291	7.780	0.680	
4	8.239	39.065	30.079	4.064	3.000	2.301	7.844	0.679	
5	8.493	38.127	30.000	4.069	3.000	2.341	8.158	0.679	
6	7.927	38.942	30.000	4.002	3.102	2.277	7.640	0.677	
7	7.309	39.440	30.000	4.000	3.000	2.203	7.150	0.677	
8	7.830	37.267	30.019	4.000	3.000	2.299	7.785	0.677	
9	8.053	38.487	30.000	4.000	3.129	2.299	7.780	0.676	
10	7.847	39.131	30.000	4.313	3.000	2.274	7.570	0.674	
11	7.980	38.877	30.002	12.00	3.000	2.276	7.549	0.673	
12	8.059	39.024	30.000	12.00	3.000	2.281	7.586	0.673	
13	7.826	39.130	30.001	12.00	3.001	2.256	7.407	0.672	
14	8.302	38.781	30.000	12.00	3.000	2.310	7.786	0.672	
15	8.022	38.946	30.000	12.00	3.014	2.280	7.568	0.672	
16	8.374	40.529	30.000	4.004	3.000	2.306	7.749	0.672	
17	7.870	38.302	30.005	12.00	3.000	2.277	7.541	0.672	
18	7.666	38.338	30.000	12.00	3.000	2.255	7.392	0.672	
19	8.503	39.204	30.021	12.00	3.000	2.323	7.863	0.671	
20	7.951	39.051	30.124	12.00	3.001	2.269	7.474	0.671	
21	6.623	37.602	30.000	4.000	3.017	2.169	6.849	0.670	
22	8.261	38.816	30.197	12.00	3.000	2.304	7.702	0.670	
23	7.697	38.519	30.000	11.86	3.000	2.261	7.393	0.670	
24	7.379	38.159	30.000	12.00	3.024	2.232	7.201	0.669	
-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	
97	8.400	38.402	30.001	4.003	8.817	2.397	7.218	0.607	
98	8.645	37.472	30.000	4.042	9.000	2.427	7.445	0.607	
99	8.216	38.811	30.000	4.207	9.000	2.376	7.051	0.606	
100	7.513	37.091	30.011	4.000	5.305	2.391	7.097	0.603	

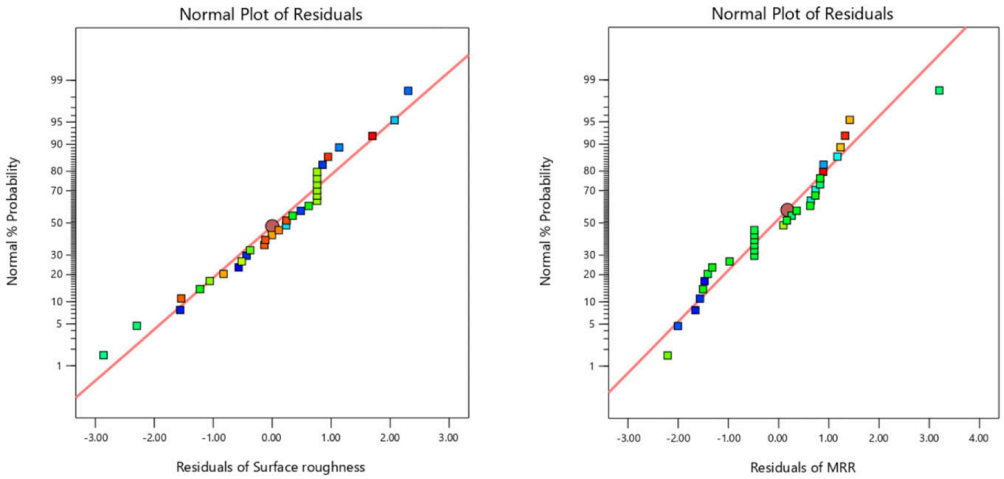


Figure 9. Normal probability plots.

https://doi.org/10.3390/engproc2026165006

4. Conclusions

This study investigates the effect of process conditions during WEDM of Nimonic 90, with the main objective of minimizing surface roughness and maximizing MRR. The key findings are outlined below:

- Pulse on time has the highest impact on surface roughness, contributing 91.73%, followed by wire tension, wire feed rate, servo voltage, and pulse off time.
- For MRR, pulse on time has the highest contribution (67.37%), followed by servo voltage, pulse off time, wire feed rate, and wire tension.
- The RSM model with a pulse on time of 7.97 µs, pulse off time of 38.48 µs, servo voltage of 30 V, wire tension of 4 N, and wire feed rate of 3 mm/min provided the optimal combination of surface roughness and MRR.
- The desirability function yielded an overall desirability of 0.68, with individual desirability values of 0.79 for surface roughness and 0.58 for MRR.
- The model showed strong predictive capability, with correlation coefficient values of 0.97 for surface roughness and 0.99 for MRR.
- The model was validated using the Anderson–Darling test and confirmation tests, with prediction errors of 5.6% for surface roughness and 8.4% for MRR.

Author Contributions: Conceptualization, U.M.R.P. and G.B.; methodology, U.M.R.P.; validation, U.M.R.P. and G.B.; formal analysis, U.M.R.P.; data curation, U.M.R.P.; writing—original draft preparation, U.M.R.P. and G.B.; writing—review and editing, U.M.R.P. and N.G.S.R.; visualization, U.M.R.P.; supervision, U.M.R.P. and N.G.S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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https://doi.org/10.3390/engproc2026165006