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Article

Investigation and optimization of process parameters in the electrical discharge machining process for Inconel 660 using response surface methodology

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ABSTRACT

Based on its exceptional mechanical and thermal qualities, Inconel 660 is a high-performance superalloy that is frequently used in marine and aerospace engineering. However, attaining the ideal material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR) is severely hampered by its low machinability. This study uses Response Surface Methodology (RSM) based on the Box-Behnken Design (BBD) to examine the impacts of different process parameters in Electrical Discharge Machining (EDM) of Inconel 660. Statistical models were created to forecast performance results, and experimental trials were carried out to optimize machining parameters. The results show that whereas pulse-off time primarily affects SR, current and pulse-on time have a considerable impact on MRR and TWR. The adjusted parameters offer improved machining performance by decreasing electrode wear and enhancing surface morphology. These insights allow Inconel 660 and related superalloys to be machined more effectively.

1. Introduction

Despite its exceptional strength, corrosion resistance, and thermal stability, superalloys like Inconel 660 are nonetheless challenging to machine [1]. When excellent mechanical performance is needed, these materials are widely used in biomedical, maritime, and aerospace applications [2]. However, traditional machining is ineffective due to its high hardness and low heat conductivity [3, 4]. A practical method for treating Inconel 660 is Electrical Discharge Machining (EDM), which offers accurate machining capabilities without causing a lot of mechanical stress [5]. Hard-to-machine materials can be shaped using EDM, a non-traditional machining technique that uses electrical sparks to dissolve the material [6]. The use of EDM on nickel-based superalloys has been the subject of numerous investigations, with an emphasis on process parameter optimization to provide increased SR, reduced TWR, and improved MRR. This work combines statistical modeling and experimental analysis to identify the ideal machining settings for Inconel 660 [7]. The nickel-based alloy Inconel 660 is utilized primarily in the marine and aviation fields [8]. Due to its extreme corrosion, resting tendency has mainly been utilized in domains like biology and nuclear sciences [9]. Many of these alloys are employed to augment the areas of the pollution control equipment [10]. These features and characteristics result in a shorter tool life during machining because, despite its positive attributes [11], it is used less frequently [12]. Because of this, using an electrode tool will eliminate high material from the workpiece [13]. The increasing use of Al-SiC composites in aerospace, automotive, and electronic industries necessitates efficient machining methods [14]. EDM is an effective non-traditional machining process for such composites, where thermal energy erodes material without direct contact. However, the presence of SiC affects EDM performance due to its electrical conductivity and thermal properties [15]. Additionally, electrode rotation enhances flushing efficiency and improves machining stability [16]. This paper examines the effect of SiC content and electrode rotation on EDM outcomes [17]. Mustafa andÇaydaş [18] examined and established characteristics of the vast majority of the influencing factors manufacturing across the testing process. With the use of an array model constructed specifically for the experiment and a pure copper anode with a tube section, Pradhan et al. [19] implemented

Abbreviations

BBD	Box-Behnken Design
EDM	Electrical Discharge Machining
MRR	Material Removal Rate
RSM	Response Surface Methodology
SR	Surface Roughness
TWR	Tool Wear Rate

the experiment. Commercial-grade paraffin had been used as the dielectric medium. After assessing the EDM experiment, Balraj et al. [20] found that utilizing graphite as the electrode provided excellent outcomes: good relative electrode wear and an adequate MRR. Utilizing input and output variables as well as mathematical models, Mohan et al. [21] evaluated several nickel-based alloy material attributes and output variables. Dhanabalan et al. [22] developed an electrical discharge machine to reproduce and examine the surface quality of machined merchandise. Further, they discovered that a white layer had grown on the surface post-surface machining. The relationship between relevant variables for the material was discovered by Luis et al. [23], who additionally generated mathematical frameworks for current, pulse length, output variables, EWR, and SR. Structural profile data for the alloy based on nickel was developed by Taweelet al. [24]. After applying and adjusting Inconel 718's those who perform well capabilities, Leera et al. [25] concluded that the Taguchi Method helped obtain the correct values. The implications of the EDM method with hybrid electrodes in nickel-based alloys were discovered. The impacts of the machining technique with composite anode in nickel-based alloys were discovered by BintiIzwan et al. [26].

The suspension nickel-based insulator medium molded polished surface was made available by Shahriet al. [27]. That form of dielectric medium takes an extensive character, following the findings of the study. Balamurugan and Gowthaman [28] demonstrated a surge in the rate of removal of metal and generated the presence of ions in a compound based on nickel with the impact of graphite powder on it. Kumar et al. [29] experimented with Electro-Discharge Machining of Inconel 718 Super Alloys. Selvarajan [30] reviewed the EDM parameter of composite material and industrial demand material machining. In their studies with the EDM approach, Shruti [31] revealed very micro pores in nickel-based alloys and discovered that electrode rotation and current were the key contributing variables, whereas the on-time pulse and current primarily impacted surface roughness. Nayim et al. [32] presented a method that generates tiny crevices in titanium and nickel-based aerospace alloys using rotary tools and tube-like copper tools. Khan et al. [33] investigated the highest output parameters obtained for powder concentration on SR, while K. Tripathy [34] examined these factors in the EDM processing of die steel. As the percentage with Silica Carbide particles boosted, the SR decreased, giving rise to a significant improvement in surface integrity. For instance, to enhance the material's surface features, Ryota et al. [35] used a mixture of chromium particles and kerosene-based oil as the medium during the EDM process. They reported that this elevated the material's corrosion resistance and surface texture. By processing a nickel-based alloy using graphite and copper materials, Choudhary and Jadoun [36] reported a comparative empirical machining method; implementing both electrodes yielded the best results. In addition to utilizing an aluminum electrode in the standard EDM process, Chinmaya et al. [37] also polished an Inconel 800 workpiece in an environment of a magnetic field on the output parameters. When the rates of electrode wear were compared and assessed, it became clear that the impact of magnetism raised the efficiency of EDM and led to better-looking machined surfaces. Kumar and Rao [38] explored manufacturing titanium-based alloys, which include powdered silicon carbide or aluminum. Concerns about different input factors, as well as how they affect output variables, have been rendered transparent by Thakur et al. [39]. Baldin et al. [40] evaluated how parameters affected the machining outcomes and ultimately found the ideal values. Dzionk et al. [41] employed a superalloy constructed from titanium and several electrode types, combining graphite-based electrodes. Sahoo et al. [42] undertook a study on a superalloy with a base as chromium to test surface integrity at different voltage and current levels. The surface roughness increases as the current rises while maintaining a constant voltage. Attempting to investigate the heating features associated with this machining process, Shandilya [43] performed the machining of titanium alloy. Mahindra and Deepak et al. [44] explored the impact of a powder mixture dielectric made up of graphite and aluminum oxide on the material Inconel 718. They found that applying graphite to kerosene oil as a dielectric raised MRR.

2. Research objectives

The primary objectives of this study were to investigate the influence of process parameters on the machinability of Inconel 660 and to optimize Electrical Discharge Machining (EDM) parameters using Response Surface Methodology (RSM) and Box-Behnken Design (BBD) to enhance Material Removal Rate (MRR), Tool Wear Rate (TWR), and Surface Roughness (SR). Additionally, the study aimed to develop predictive models that facilitate efficient machining process planning and validate the experimental findings through statistical analysis and empirical testing.

3. Methodology

The pilot examinations with one fixed-at-a-time planning helped find appropriate input variable values for this machining process. While initiating the experiment, a specific rate of supplied parameters is taken, and their range is defined. This is achieved by an ordered experimental performance. One of the most important steps for achieving the desired outcomes is correctly selecting the input variables, shown in Table 1, and fixing their ranges. It additionally makes it possible to utilize fewer experimental outputs than desirable when the machining is done. Subsequent experimentation was carried out using what came out of this descriptive experiment. Thus, utilizing the one fixed-at-a-time (OFAT) approach method establishes proper parameters to be exploited and the perfect range for this main experiment. The various kinds of Inconel alloy A 286 sheets, each measuring 65 mm by 120 mm by 3 mm, are utilized for pilot and research purposes, respectively. The intervals that followed were determined to be significant. All three stages of parameters are applied to generate the model. The layout experiment is created using the Box Bekhen Design method. Current, pulse-on time and pulse-off time were among the machining parameters that were adjusted within predetermined ranges. The trials were effectively structured using a Box-Behnken Design (BBD). The electrode's aspects specifications are 10 mm in diameter and 60 mm in length. Optical profilometers are employed in the assessment of surface integrity. The initial weight-final weight difference has been utilized to calculate MRR and EWR. The Taylor Hobson 3D optically surface profilometer is the tool used to determine surface roughness and assess surface integrity. This profilometer intends to measure fully symmetric surfaces, including lenses and free-form continuum surfaces, with great accuracy without requiring contact. Improved precision is a need for various applications. Thus, it is employed to obtain the roughness measurements for uneven terrain, sloping surfaces, and changeable pitch.

Table 1. Set values for the conduction of the experiment based on the Pilot Run

S.No.	Parameter	Level(-1)	Level(0)	Level(+1)
1.	Current	7.60	9.25	10.78
2.	Pulse on Time	250	350	550
3.	Pulse off Time	150	200	250

4. Results and discussion

The experiment employed the RSM-based BBD (Box Bekhen Design) approach method and employed copper electrodes. Three inputs of each input parameter for the experimental performance were taken, and each experiment lasted ten minutes. After computation, the outcomes are shown in Table 2. In every conducted experiment, the weight differences were calculated. There are three stages to each experimental run, and at each level, various parameter values are obtained for optimization and analysis. The response variables MRR, TWR, and SR were measured throughout 17 experimental runs. Analysis of Variance (ANOVA) was used to assess the statistical significance of each parameter's impact on the gathered data.

Table 2. Experimental Output

		Input parameters			Output parameters		
Std	Run	F1 current	F2 pulse on time	F3 Pulse off time	EWR	MRR	SR
16	1	9.25	350	200	21.0062	0.7503	0.4623
3	2	7.60	550	200	21.0038	0.0115	1.0575
13	3	9.25	350	200	21.0063	0.7505	0.3652
6	4	10.78	350	150	21.0012	1.5581	0.8487
15	5	9.25	350	200	20.9866	0.7503	0.3565
12	6	9.25	550	250	20.9843	1.1008	0.4254
10	7	9.25	550	150	20.9788	0.8258	0.3321
8	8	10.78	350	250	20.9751	3.7768	0.6921
7	9	7.60	350	250	20.9728	0.8032	0.6325
17	10	9.25	350	200	20.9648	0.7490	0.5656
14	11	9.25	0350	200	20.9623	0.7440	0.4674
9	12	9.25	250	150	20.9591	0.7095	0.6385
5	13	7.60	350	150	20.9542	0.7811	0.6151
11	14	9.25	250	250	20.9515	1.8674	0.4978
4	15	10.78	550	200	20.9471	2.4023	0.2384
2	16	10.78	250	200	20.9327	2.8208	0.7985
1	17	7.60	250	200	20.9269	0.7407	0.5756

4.1 Evaluation and optimization of TWR, MRR, SR

Table 3 below demonstrates how much of a significant 8.25 F-value model was developed for the generated model. Disturbances had more value of F- less value of 0.41% probability of occurring. According to the model, P- lower than 0.052 values are significant. The generated sources are significant; the terms A, AB, AC, and A^2 have very valuable model values. The ANOVA results indicate that current is the most significant factor for MRR ($p < 0.01$), while TWR is significantly influenced by the interaction between current and pulse-off time. The model demonstrated strong predictive accuracy, with an R^2 value exceeding 90% for all response variables. Table 4 indicates how significant the ANOVA (analysis of variance) is for the Rate of Material Removal, with a Model F-value of 57.33 when utilizing ANOVA. The probability is less than 0.01% of an F-value disruption due to noise. The defined model is significant for the supplied P-values lower, as indicated by the 0.0500. In this instance, the majority of the terms produced are essential. It is impossible to reach the 0.1000 values indicated as having significant values.

Table 3. ANOVA for electrode wear rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0303	9	0.0025	8.25	0.0043	significant
A-Current	0.0064	1	0.0085	17.48	0.0039	
B-T(on)	0.0013	1	0.0014	0.7688	0.3756	
C-T(off)	0.0015	1	0.0016	0.27	0.2862	
AC	0.0057	1	0.0059	11.00	0.0116	
BC	0.0087	1	0.0088	34.54	0.0020	
A^2	0.0001	1	0.0013	0.5136	0.6311	
C^2	0.0041	1	0.0063	11.61	0.0087	
Residual	0.0005	1	0.0015	0.8538	0.3659	
Lack of Fit	0.0022	1	0.0023	3.85	0.1478	
Pure Error	0.0024	7	0.0006			
Cor Total	0.0039	3	0.0010	234.13	<0.0001	significant

Table 4. ANOVA for material removal rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	13.62	7	1.19	57.33	< 0.0001	significant
A-Current	8.26	1	7.39	238.45	0.0082	
B-T(on)	0.4832	1	0.4832	12.57	0.0051	
C-T(off)	1.96	1	1.58	48.50	0.0065	
AC	1.24	1	1.31	36.17	0.0003	
BC	0.2256	1	0.2368	8.86	0.0295	
A^2	1.54	1	1.84	51.29	< 0.0001	
C^2	0.3875	1	0.3658	10.58	0.0098	
Residual	0.3305	9	0.0425			
Lack of Fit	0.0003	5	0.00005	3.09	<0.0001	
Pure Error	0.0000	4	7.557E-06			
Cor Total	15.65	16				

Table 5 displays the ANOVA for MRR; the model F-value, 2.29 in this particular model, indicates significance. Noise caused the F-value of 14.22%, which indicates that the 0.0555 P-values produced had significant values. The model terms demonstrate that the conditions AB and A2 are important. The significant model is illustrated by the utility of 0.1422.

Table 5. ANOVA for surface roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.6150	9	0.0689	2.30	0.1422	not significant
A-Current	0.0127	1	0.0114	0.3845	0.0555	
B-T(on)	0.0254	1	0.0256	0.8589	0.3842	
C-T(off)	0.0199	1	0.0185	0.6428	0.4854	
AC	0.3158	1	0.3276	10.81	0.0125	
BC	0.0182	1	0.0183	0.6024	0.4532	
A^2	0.0039	1	0.0046	0.1509	0.7196	
C^2	0.2118	1	0.2108	6.95	0.0321	
Residual	0.0106	1	0.0116	0.3835	0.5525	
Lack of Fit	0.0018	1	0.0020	0.0674	0.8015	
Pure Error	0.2021	7	0.0303			
Cor Total	0.1718	3	0.0605	7.90	0.0345	significant

4.2 Mathematical expression and regression analysis

The actual expression developed for the conducted experiment for the EWR is:

$$EWR=+0.035740+0.040450*Current+0.007723*T(on)-0.007023*T(off)+0.035875*Current*T(off)-0.025*T(on)*T(off)+0.006450*Current^2+0.035030*T(off)^2 \quad (1)$$

The actual expression developed for the conducted experiment for the MRR is:

$$MRR=+0.863752+1.01870*Current-0.656425\ T(on)+0.454125\ T(off)+0.564185Current*T(off)-0.245625T(on)*T(off)+0.665771\ Current^2+0.458271\ T(off)^2 \quad (2)$$

The actual expression developed for the conducted Experiment for the SR is:

$$SR=+0.631000-0.042012*Current-0.054012*T(on)-0.049725*T(off)-0.275200*Current*T(on)-0.064575 \quad (3)$$

Higher current increases MRR but also EWR and can worsen SR at high values. Increasing pulse-on time decreases MRR and improves SR but has a minimal effect on EWR. Pulse-off time improves MRR and reduces SR but has a slight negative impact on EWR. Interaction effects are crucial in determining machining performance, meaning optimal EDM settings require balancing these parameters. Figure 1 displays the expected and actual values of the electrode wear rate. The graph demonstrates that the theoretical values created during the experimental performance are consistent and can be readily verified by observing the plot of the actual values to the predicted values. Since the points are well-aligned with the line, your model has a strong predictive capability with minimal deviation. If there were significant deviations, it would suggest model errors or areas where predictions need refinement.

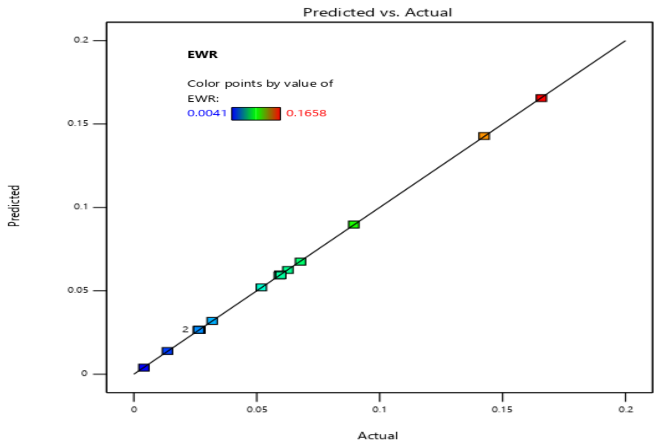

Figure 1. Predicted vs. actual graph for TWR, validating model accuracy

The output variable, the material removal rate, is shown by the manifest predicted value versus the experimental value in Figure 2. It validates that the actual model of MRR generated is adjacent and near to the expected theoretical solutions developed at the conduction of the experimental procedure, as the graph clearly demonstrates.

The expected & experimental results of surface integrity are shown in Figure 3. From the graph genuine to the estimated value actual line, validated in the actual model of SR. It is established in close proximity, as shown in the graph. Since the points closely follow the diagonal, the model has minimal deviation and substantial predictive accuracy. Any major deviations from the line would indicate prediction errors, but none are visible here.

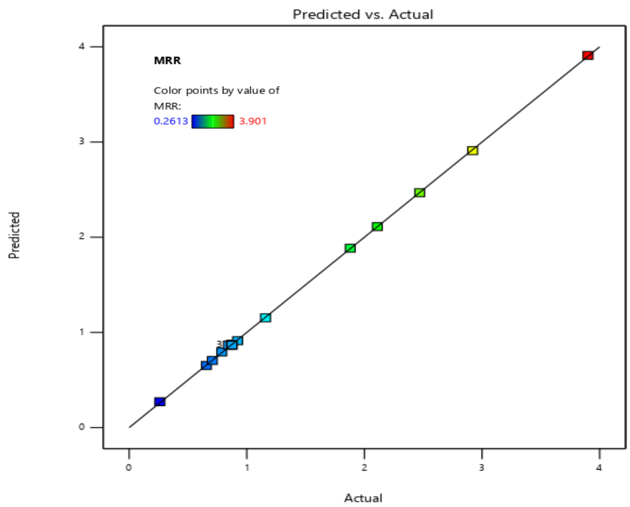

Figure 2. MRR model validation through predicted vs. actual values

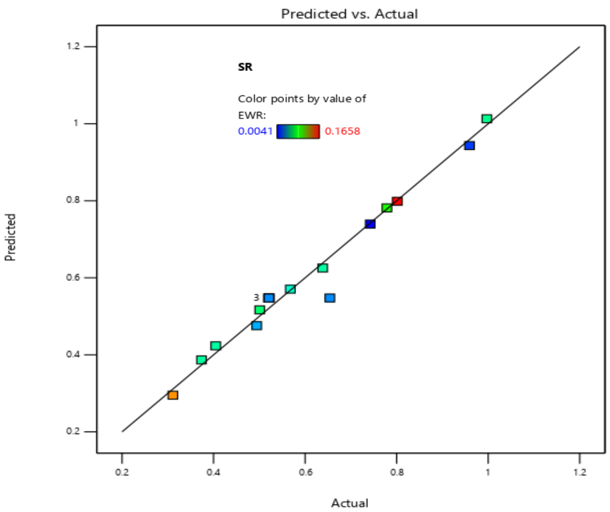

Figure 3. SR analysis, demonstrating consistency between experimental and predicted values

Figure 4 illustrates the EWR perturbation plot, which will bolster the impact of additional parameters in the design. The output parameter is displayed as fluctuating between each value and the other value components. The characteristic plot displayed a steep inclination, indicating that the input variables were very responsive to the output parameter component, Electrode wear Rate. Plotline proximity indicates reduced sensitivity to changes in that specific factor. This suggests that EWR increases significantly when factor A increases, meaning Factor A strongly influences electrode wear.

The perturbation plot of the MRR in Figure 5 illustrates how various design parameters may have an impact. The output parameter is displayed as fluctuating between all values and additional value components. The characteristic plot displayed a steep inclination, indicating that the input variables were very responsive to the output parameter component, Electrode wear Rate. Plotline proximity indicates reduced sensitivity to changes in that specific factor.

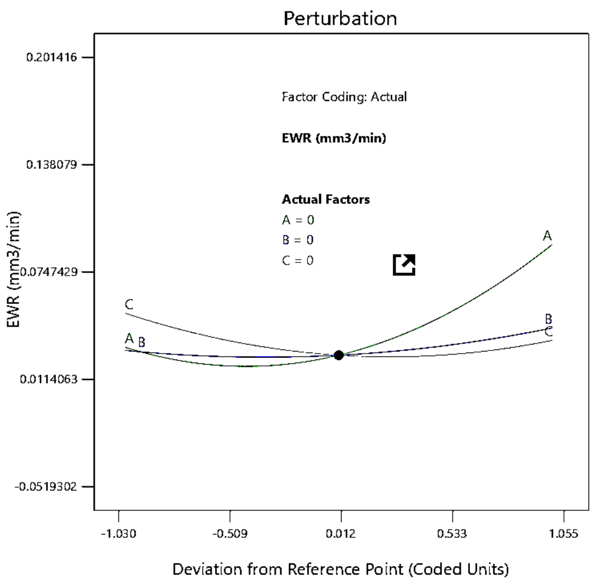

Figure 4. Perturbation plots showing the influence of different machining parameters of EWR

The SR perturbation plot in Figure 6 illustrates which will bolster the impact of additional parameters in the design. The output parameter is displayed as fluctuating between all values that it possesses together with additional value components. The characteristic plot displayed a steep inclination, indicating that the input variables were very responsive to the output parameter component, Electrode wear Rate. Plotline proximity indicates reduced sensitivity to changes in that specific factor.

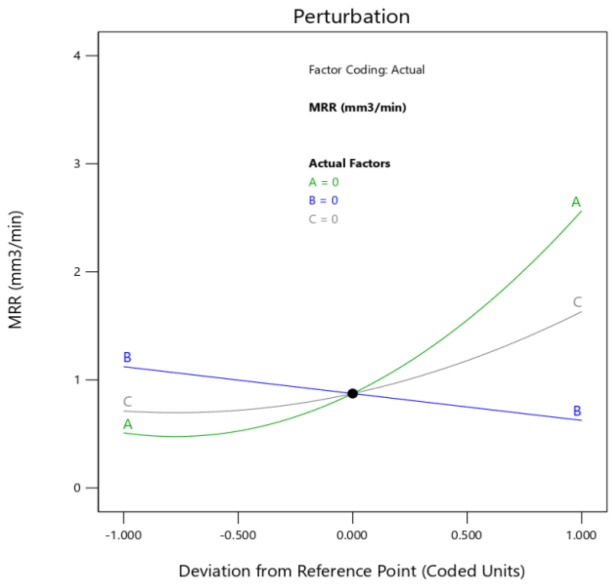

Figure 5. Perturbation plots showing the influence of different machining parameters for the MRR

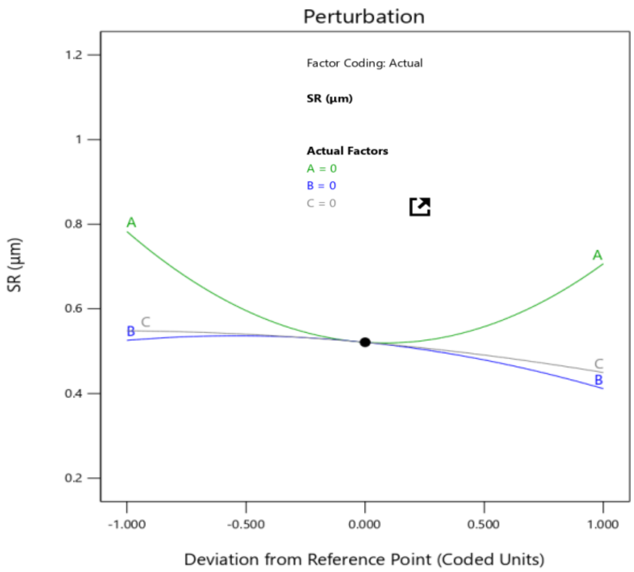

Figure 6. Perturbation plots show the influence of different machining parameters on the SR

4.3 Multi-response optimization

By optimizing the Design Expert software, the output and input factors are displayed in Table 6 according to the model being used. This instance emphasizes the necessity of considering each output and maximizing the variables to get the most out of all output variables. Tables from the numerical report's modification have been included; the first table provides an overview of limitations taken into account to generate the second table, including lists of the process's ideal responses. By employing a copper electrode to machine the Inconel alloy A 286, the ideal values for each of the parameters when the electrical discharge process of machining was found to be current = 11.233A, pulse on duration time = 220.65μs, and pulse off duration time = 70.9μs for the output variables.

The optimized results in Table 7 show that a lower EWR is desirable as it prolongs the tool electrode's life. The given value indicates minimal electrode degradation. A high MRR is generally preferred in machining to improve productivity. The optimized parameters ensure an effective balance between high MRR and low wear. A lower SR indicates a smoother surface finish. The achieved roughness is relatively low, which is beneficial for applications requiring high precision. The machined workpiece is shown in Figure 7.

The figure shows an Electrical Discharge Machining (EDM) workpiece with several machined craters or cavities. Variations in parameters cause surface roughness (SR) changes, with some machined places appearing smoother and more uniform and others seeming rougher and darker. It appears that certain parameters led to larger material removal rates (MRR) than others, based on the contrast between the crater diameters and depths. A higher electrode wear rate (EWR), which may be impacted by excessive current or ineffective debris flushing or carbon deposition, may cause certain craters' darker appearance. Different machining circumstances were tried, potentially adjusting factors including current, pulse-on time, and pulse-off time, as indicated by the numbered markings next to each machined region.

Table 6. Optimization of parameters

Parameter	Goal	Low Limit	High Limit	Lower Weight	Upper Weight	Importance
A: Current	Within range	-1	1	1	1	3
B:T(on)	Within range	-1	1	1	1	2
C:T(off)	Within range	-1	1	1	1	2
MRR		0.0123	3.8895	1	1	3
EWR		0.0061	0.165	1	1	3
SR		0.2387	1.2658	1	1	2

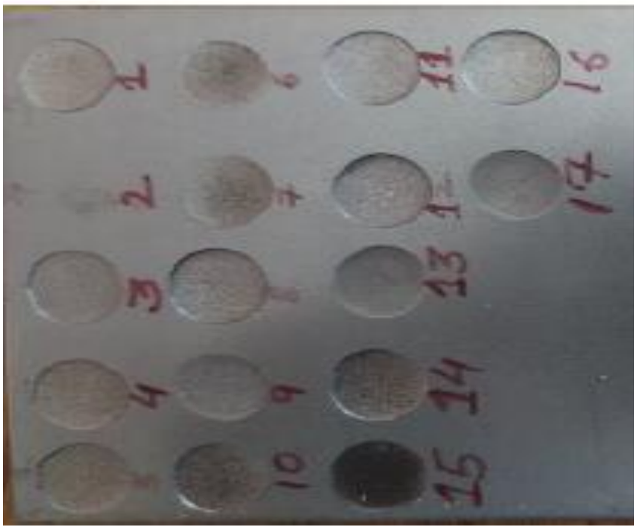

Figure 7. Machined workpiece image, providing visual confirmation of the optimized parameters

5. Conclusion

To overcome the difficulties brought on by Inconel 660's poor machinability, this study effectively adjusted the EDM process parameters for machining it. While pulse-off time is important in SR, current and pulse-on time have a major impact on MRR and TWR. The regression models that were created offer reliable forecasts for machining results. Optimized settings improve surface smoothness, decrease electrode wear, and increase machining efficiency. These findings provide important insights for industrial applications and advance our understanding of EDM processing for superalloys. For even more machinability and energy efficiency gains, future studies should investigate the incorporation of hybrid EDM techniques.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Table 7. Optimized results

S.No.	Current(A)	Pulse on time(μs)	Pulse off time(μs)	EWR(mm³/min)	MRR(mm³/min)	SR(μm)	Desirability
1.	11.233A	220.65μs	70.9μs	0.077	2.523	0.4678μm	1

Conflict of interest
The authors declare no potential conflict of interest.

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