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An Experimental Study on the Nimonic-90 Superalloy using the WEDM Process

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Abstract
Wire electro discharge machining (WEDM) is an uncommon machining technology that uses spark erosion to make complex forms out of a wide range of exotic materials, irrespective of their hardness. During Nimonic-90 WEDM, two response variables-rate of material removal (MRR) and surface roughness (SR)-were simulated together with five input process parameters: pulse on time (Ton), peak current (IP), wire tension (WT), pulse off time (Toff), and wire feed rate (WF). It is a nickel-base superalloy with high rupture strength at high temperatures and resistance to creep. The workpiece was cut using an electrode that was a 0.25 mm brass wire. A single-replicate L27 orthogonal array is employed for process optimization and regression model development, including process parameter–response parameter correlations.

Keywords: *WEDM; Nimonic-90; L27; Material Removal Rate; Surface Roughness*

1. Introduction

Wire electrical discharge machining (WEDM) is a method that employs the use of a wire to sculpt extremely intricate shapes onto electrically conducting work components. "Spark erosion machining" is another name that is occasionally used to refer to WEDM. Material is removed from the workpiece by means of discrete sparks that are generated between the anode (the workpiece) and the cathode (the wire electrode). Deionized water is used as a dielectric fluid which separates anode and cathode and continuously flushing away the debris generated due to machining (Sarkar et al., 2008). The better surface quality and high level of dimensional accuracy of the workpiece that can be achieved with WEDM are primarily required for applications in the aerospace, chemical, dies and moulds, medical and surgical, automotive, and other industries. Wire EDM is the best, and sometimes only, option for cutting exotic, conductive, and difficult-to-machine materials with the ability to generate complicated forms and profiles(Sarkar et al., 2008). Due to wide application in industry, production engineers need a trustworthy model to predict the output response of WEDM process.

The wire electro discharge machining process has been modelled by a number of researchers using various methods. Using the utility approach, Goswami and Kumar proposed a multi-objective optimisation strategy for WEDM machining of Nimonic-80A alloy. The features under investigation include machined surface topography, MRR, and SR. The research followed Taguchi's robust design methodology in both its planning and execution. Ton, Toff, SV (spark gap set voltage), IP, WF, and WT were six input process variables that were manipulated at three separate levels during the trials (Goswami & Kumar, 2014). Using RSM (response surface methodology), Kumar and Nishasoms analysed the machining characteristics of an Al (6082)/tungsten carbide composite for WEDM. The variables employed to analyse the MRR and SR were IP, Ton, Toff, WF, and tungsten carbide percentage. The influence on MRR and SR is investigated using the analysis of variance technique (Ravi Kumar & Nishasoms, 2019).

Xavior et al. (Anthony Xavior et al., 2018) evaluated the influence of the RCL (recast layer) created during electric discharge machining of Inconel 718 on the fatigue life of workpiece at room temperature. The results of four distinct parameters with three levels of experimentation are derived using Taguchi's L9 orthogonal array. IP, Ton, SV and Toff are the variables that are changed. While employing the WEDM technique to cut pure tungsten profiles, Yang et al. looked at changes in the MRR, SR, and CD (corner deviation). An integrated SAA (simulated annealing algorithm) and RSM (back-propagation neural network) hybrid technique was introduced to determine the optimal parameter setting. In order to train the BPNN to predict the MRR, SR, and CD features, 18 experimental runs were chosen from the Taguchi orthogonal table (Yang et al., 2012).

Kumar and Chalisgaonkar spoke on how to use the utility technique to build a multi-response optimisation model that can predict and find the best WEDM machining parameter settings. Working with process parameters including Tonne, WF, Toff, IP, WT, and SV, experiments were conducted using pure titanium in the WEDM process. For this set of trials, the L27 orthogonal array was used. The most effective way to define the process parameters for CS and SR was to use multi-response optimisation based on the utility idea. They utilised analysis of variance (ANOVA) to rank the parameters according to how much of an effect they had on the CS and SR (Chalisgaonkar & Kumar, 2013). The effect of Toff, IP, Tonne, and SV—four WEDM process variables-on the machining of the Nimonic-263 alloy was examined by Rao and Venkaiah. An experimental plan had been implemented using a central composite face cantered design of RSM. The significance of the process parameters was determined using ANOVA analysis (Sreenivasa Rao & Venkaiah, 2015). Using RSM in conjunction with the desirability function for multi response optimisation, V. Kumar et al. analysed the effect of process variables on three response parameters-CS, SR, and RoC-during the machining of Nimonic-90 on a WEDM (Kumar et al., 2016).

Raju and Balakrishnan (Raju & Balakrishnan, 2020) discussed the optimal parameters setting for a high rate of material removal with a good surface finish. The material chosen for this study was an aluminium metal matrix composite made by stir casting with 90% Al 6061 and 10% Boron Carbide as reinforcement. The Ton, IP, and Toff parameters were chosen for the study, which was carried out on a WEDM. According to BBD (Box Behnken Design), operating parameters with three levels were chosen. SR and MRR were taken into consideration as output responses for the experiment. Chakraborty and Bose (Chakraborty & Bose, 2017) found the best cutting settings using entropy-based GRA. SV, Tonne, CA (corner angle), SF, IP, and Toff were used to calculate Inconel 718 machining output responses such cutting velocity, SR, MRR, and corner inaccuracy.

Extensive study has been conducted on wire EDM utilizing various conductive metals. The material known as Nimonic-90 is attracting interest due to its exceptional strength at high temperatures, remarkable resistance to corrosion, and low thermal conductivity. Because of these distinctive attributes, it finds significant utility in the aerospace sector for applications like as jet engines, valves, blades, and so on (Kumar et al., 2012). The combination of low thermal conductivity and high temperature strength poses challenges in machining heat resistant metals. Conventional machining techniques face significant difficulties when used for the machining of Nimonic-90. WEDM, a contemporary machining technique, is being progressively utilized to process extremely tough materials (Kumar et al., 2012).

With every WEDM, there is insufficient operational data. This data is insufficient to machine all types of material; performance analysis is necessary to identify the ideal setting of variables at which quality and production may coexist. Therefore, this study concentrated on WEDM machining of Nimonic-90. The focus of the current work is on the creation of mathematical models that correlate the effects of different WEDM parameters such as IP, Ton, WT, Toff, and WF, on the MRR and SR for Nimonic-90 material. L27 OA from Taguchi's design of experiments is selected for experimentation. The results of this work would be very helpful to develop performance charts of Nimonic-90 alloy for WEDM which are not readily available.

2. Materials and methods

In the sections below, the workpiece material, experimental setup, experiment design, and measuring tools have all been discussed.

2.1. Workpiece Material

Nimonic-90 material was purchased from M/s PRASHAANT STEEL, Mumbai, in order to conduct the experiments. Table 1 displays the chemical composition of Nimonic-90. It melts at 1370 degree Celsius, has a hardness of 365 HV, a thermal conductivity of 11.47 W/m°C, and a modulus of elasticity of 220 MPa. Its density is 8.18 g/cm^3. Nimonic-90 is characterised by its strong rupture strength and good creep resistance at high temperatures (up to 920°C). All experiments are conducted using workpiece material with a thickness of 10 mm. Punches measuring 8 mm * 5 mm * 10 mm were cut from the work piece using a wire electrode of 0.25 mm diameter made from brass.

Table 1. Chemical composition of Nimonic-90 superalloy

Element	Cr	Co	Ti	Al	Fe	Mn	Si	C	Cu	B	Zr	Ni
Requirements %	18≥0≤21	15≥0≤21	2≥0≤3	1≥0≤2	≤1.50	≤1	≤1	≤0.13	≤0.20	≤0.02	≤0.15	Balance
Actual %	18.79	18.63	2.50	1.30	0.18	0.002	0.003	0.090	0.003	0.001	0.005	58.39

2.2. Experimental details

For the studies, the 4-axis Electronica Sprint Cut-734 WEDM machine is utilized. To study the effects on MRR and SR, the experiment involves modifying the process parameters including Toff, Ton, WF, IP, and WT. The material and wire diameter are maintained constant during the machining process. The anode (+ve terminal) is linked to the work piece, while the cathode (-ve terminal) is connected to the wire. The dielectric fluid maintains a separation between the electrode and the workpiece. The productivity of machining is determined by the MRR. It can be found using the following relation (Goswami & Kumar, 2016):

MRR (mm^2/min) = (perimeter of cut × thickness of plate) / Time of cut (1)

The surface roughness (Ra) is measured with a contact type roughness tester, the Mitutoyo Surftest SJ-410, which has a minimum count of 0.001 μm. The evaluation length kept to 4 mm, while the cutoff length for measurements is set at 0.8 mm. The average value of SR is determined by taking a mean reading from three different sites that are all facing vertically in the direction of the cut. This is done to get the Ra value. Fig. 1 shows the setup for the SR measurement.

Fig. 1. Surface roughness measurement apparatus

2.3. Machining parameters with their levels

The present investigation examined the impact of various input variables, including Ton, Toff, IP, WF, and WT, on response variables including MRR and SR. A determination of the input process variable levels was made in accordance with the capabilities of the machine, the manufacturer's manual, and review of the relevant literature. Table 2 contains a list of the controlled process variables, along with their corresponding coded values.

Table 2. Descriptions and ranges of process variables

Coded Parameters	Real Parameters	Parameters' Symbolic Name	Levels		
			1	2	3
A	Pulse on Time	Ton	106	114	122
B	Pulse off Time	Toff	35	45	55
C	Peak Current	IP	100	160	220
D	Wire Feed Rate	WF	6	9	12
E	Wire Tension	WT	4	6	8

2.4. Design of Experiments

Taguchi's proposed experimental design makes use of orthogonal arrays. The process-affecting factors are grouped in an orthogonal array according to their levels. Unlike the factorial design, which examines every possible combination, the Taguchi technique only evaluates specific pairs of possibilities. Because of this, less experimenting is needed to find the input variables that have a significant impact on the output, which saves time and money. This technique provides the greatest tool for designing parameters for performance characteristics. For the purpose of optimizing the performance characteristic, new parameter values can be chosen using ANOVA on the obtained data (Jangra et al., 2014). Five different process parameters were chosen for this research from the currently available literature on WEDM.

Five control parameters—WT, Toff, IP, WF, and Ton—were tested using an L27 orthogonal array with a single replication in this investigation. S/N (signal-to-noise) ratio was calculated using Minitab 16 software. In order to obtain the best possible machining characteristics, HB was selected for MRR (higher is better) and LB for SR (lower is better). Equations 2 and 3 may be used to compute the signal-to-noise ratio by transforming the loss function logarithmically (Goswami & Kumar, 2014).

$$S/N_{MRR} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (2)$$

$$S/N_{SR} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (3)$$

The computed S/N ratios for MRR and SR are depicted in Figs. 3 and 5, respectively. The performance metrics of MRR and SR with the L27 orthogonal array are displayed in Table 3.

Table 3. Performance measure of MRR and SR

STD Order	Process Parameters					Response-1		Response-2	
	Ton	Toff	IP	WF	WT	MRR-1 (mm^2/min)	MRR-2 (mm^2/min)	SR-1 (μm)	SR-2 (μm)
1	106	35	100	6	4	7.491	6.813	1.5393	1.4280
2	106	35	100	6	6	7.718	7.239	1.5118	1.4785
3	106	35	100	6	8	9.562	9.614	1.6133	1.4220
4	106	45	160	9	4	11.268	11.438	1.8020	1.6268
5	106	45	160	9	6	11.572	12.443	1.7128	1.6373
6	106	45	160	9	8	13.426	13.274	1.8663	1.7138
7	106	55	220	12	4	7.444	7.513	1.5630	1.4655
8	106	55	220	12	6	6.845	7.145	1.5183	1.5893
9	106	55	220	12	8	9.937	9.150	1.5458	1.5540
10	114	35	160	12	4	15.066	16.662	2.6553	2.6245
11	114	35	160	12	6	16.558	17.315	2.5388	2.3483
12	114	35	160	12	8	18.496	20.812	2.5628	2.7460
13	114	45	220	6	4	21.329	22.898	2.4118	2.4823
14	114	45	220	6	6	24.042	26.774	2.5485	2.6588
15	114	45	220	6	8	29.885	25.067	2.6663	2.7760
16	114	55	100	9	4	14.672	12.867	2.4710	2.3905
17	114	55	100	9	6	13.333	13.008	2.5675	2.3668
18	114	55	100	9	8	14.599	13.312	2.5740	2.4563
19	122	35	220	9	4	25.952	25.641	2.9830	2.9045
20	122	35	220	9	6	31.195	31.877	3.1930	3.4150
21	122	35	220	9	8	29.082	28.401	3.2585	3.1253
22	122	45	100	12	4	23.821	27.317	2.9820	2.9000
23	122	45	100	12	6	24.262	28.430	3.3463	3.1373
24	122	45	100	12	8	28.918	29.512	3.1820	3.2463
25	122	55	160	6	4	20.937	21.194	3.0140	2.9755
26	122	55	160	6	6	22.310	21.443	2.8105	2.7605
27	122	55	160	6	8	20.918	20.345	3.0530	2.9810

3. Results and discussion

It is important to assess the adequacy of the model derived from experimental data. An ANOVA was conducted to assess the validity of the estimated model.

3.1. Analysis of material removal rate (MRR)

By employing the ANOVA test on the experimental data, we were able to ascertain with precision the relative importance of the process variables in relation to the response parameters. The F-test is a statistical method used to determine whether the parameters selected for the study have a significant impact on the response or not. Responses are recorded with a predetermined degree of confidence in controlled experimental environments. A higher F value indicates that the relationship between the process parameter and the response parameter is statistically significant (Dabade & Karidkar, 2016). If the estimated F value of the selected parameter is higher than the $F_{\alpha,v1,v2}$ value (where α is the risk and v1 and v2 are degrees of freedom), then the input process parameter significantly affects the response characteristics (Chalisgaonkar & Kumar, 2013).

An ANOVA analysis was performed on the experimental data for MRR. From Table 4, it is evident that variables, including Ton (74.57%), Toff (14.44%), and IP (6.03%), have a profound influence on MRR, which is statistically significant at the 95% confidence level. The results of the analysis show that Ton and Toff are the most effective machining variables (Chalisgaonkar & Kumar, 2013).

Table 4. Analysis of Variance for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	p-value Prob >	Percent of contribution %
Ton	2	2379.28	2379.28	1189.64	513.29	0.000*	74.57
Toff	2	460.78	460.78	230.39	99.41	0.000*	14.44
IP	2	192.43	192.43	96.21	41.51	0.000*	6.03
WF	2	4.79	4.79	2.39	1.03	0.364	0.15

WT	2	53.80	53.80	26.90	11.61	0.000*	1.69
Error	43	99.66	99.66	2.32			
Total	53	3190.73					

Note: * – significant at 95% level

3.1.1. Mathematical model for MRR in WEDM process

A mathematical model to relate the MRR in WEDM with selected machining variables, including Ton, Toff, IP, and WT, has been developed. Based on the test results obtained through the previously described experimental strategy, the resulting mathematical model is as follows: In the Equation 4, the insignificant variables have been left out:

$$MRR = -98.4 + (1.01 * Ton) - (0.190 * Toff) + (0.0360 * IP) + (0.611 * WT) \quad (4)$$

Fig. 2 demonstrates that the MRR increased from 9.4385 mm^2/min to 25.642 mm^2/min when the Ton increased from 106 to 122 mu. In this case a higher Ton extends the duration of the discharge energy, which causes material to rapidly melt and evaporate. As a result, a lot of material is removed. Similar kind of results was reported by Goswami, A (Goswami & Kumar, 2014). As may be observed in Fig. 2, the MRR increased from 16.2493 to 20.5655 mm^3/min when the IP increased from 100 to 220 mu. A higher value of IP yields more discharge energy, resulting in the overheating and vaporization of metal. Due to these factors, the application of high-pressure energy results in the formation of substantial craters on the surface being worked on. This leads to the elimination of a substantial quantity of substance (Goswami & Kumar, 2014). It can be seen from **Error! Reference source not found.**2 that MRR rises as Toff decreases. When Toff increases the number of discharges in a specific period reduces. Due to that, the work piece is subjected to less discharge energy in a given period of time, which lowers the rate of metal erosion and reduces the MRR. According to the experimental findings, as shown in Fig. 2, wire tension has little to no impact on MRR. The tightness and straightness of the wire generate a modest improvement in MRR after increasing WT (Goswami & Kumar, 2014).

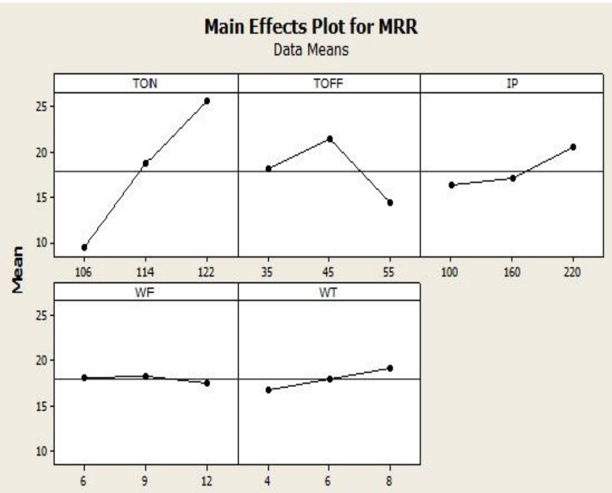

Fig. 2. Main effects plot for MRR

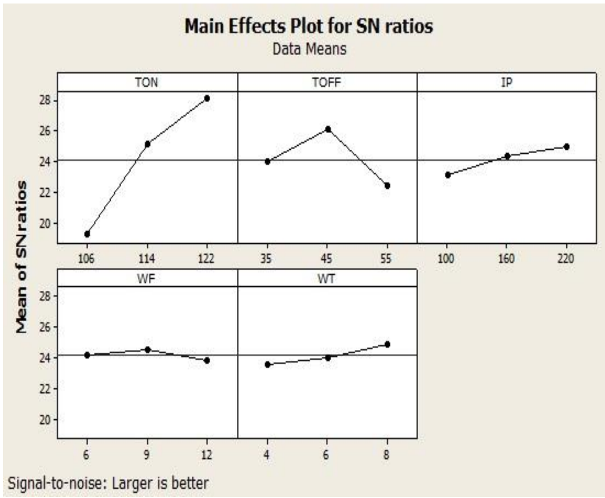

Fig. 3. SN ratios of MRR

3.2. Analysis of Surface Roughness (SR)

An ANOVA test is applied to the collected experimental results in order to assess the model's adequacy. Table 5 represents the ANOVA analysis for the SR at the 95% confidence level. It is apparent that factors like Ton (94.96%) have a considerable impact on SR, which is statistically significant at a level of 95%. It is evident from the above data that Ton is the most effective parameter (Chalisgaonkar & Kumar, 2013). With the exception of IP, all factors were determined to be significant at a confidence level of 95%.

Table 5. Analysis of Variance for SR

Source	DF	Seq SS	Adj SS	Adj MS	F	p-value Prob > F	Percent of contribution %
Ton	2	20.3417	20.3417	10.1708	792.66	0.000*	94.96
Toff	2	0.2578	0.2578	0.1289	10.04	0.000*	1.20

IP	2	0.0336	0.0336	0.0168	1.31	0.281	0.16
WF	2	0.1100	0.1100	0.0550	4.29	0.020*	0.51
WT	2	0.1260	0.1260	0.0630	4.91	0.012*	0.59
Error	43	0.5517	0.5517	0.0128			2.58
Total	53	21.4207					

Note: * – significant at 95% level

3.2.1. Mathematical model for SR in WEDM process

One may now use a mathematical model to relate the SR in WEDM with different machining parameters, including Ton, Toff, WF, and WT. Based on the test results generated through the previously described experimental strategy, the resulting mathematical model is shown below. In the Equation 5, the insignificant variables have been left out:

$$SR = -8.24 + (0.0926 * Ton) - (0.00470 * Toff) + (0.0127 * WF) + (0.0295 * WT) \quad (5)$$

SR is significantly influenced by the functions of WT, Ton, Toff, and WF which are also able to predict surface roughness within a given range of control parameters. From the analysis, it is determined that the major effects of a Ton, Toff, WT, and WF are statistically significant for this investigation. Fig. 4 shows that the surface roughness is minimized for small values of Ton. This is because materials melt and evaporate at a faster rate when Ton is larger, since the discharge energy duration increases with Ton. Consequently, the work surface is marked by large craters caused by high-pressure energy. As the value of Ton increases, the crater will get deeper and larger, which will result in an increase in the value of SR (Goswami & Kumar, 2014). From Table 5, it can be seen that Ton, with a contribution of 94.96%, is the machining variable that has the greatest impact among all significant parameters of the SR.

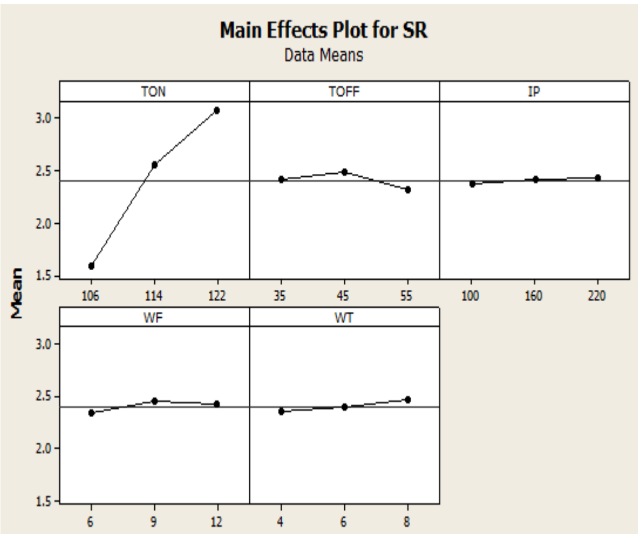

Fig. 4. Main effects plot for SR

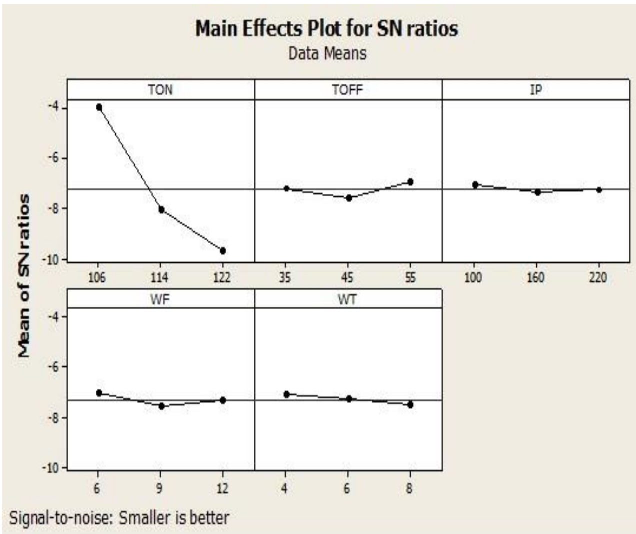

Fig. 5. SN ratios of SR

4. Confirmation Test

A confirmation test is performed to verify the model created for the performance measures provided by Equation 4 and 5. Confidence intervals around the predicted mean have been established and mean performance characteristics have been estimated using the Taguchi technique. For every performance characteristic, three confirmation trials were conducted at the optimal machining parameter settings, and the mean value was reported. The median values of the performance characteristics acquired from the validation trials must be included in the 95% CI_{CE} (Chalisgaonkar & Kumar, 2013).

The following equation was used to determine the CI_{CE}.

$$CI_{CE} = \sqrt{F_\alpha(1, f_e) MS_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (6)$$

Where,

$F_\alpha(1, f_e)$ = F-ratio at (1 – α) confidence level against DOF 1 and error degrees of freedom.

MS_e = mean square error

$$\eta_{eff} = \frac{N}{1 + DOF_{total}}$$

N = N = total experiments

DOF_{total} = sum of significant variables DOF.

R = number of repetitions for the confirmation test

See the values given in Table 6. It has been discovered that the confidence intervals sufficiently cover the mean values of the test results. Manufacturing engineers may use these findings to forecast the values of response parameters like MRR and SR for the WEDM of Nimonic-90 super alloy using these data.

Table 6. Confirmation test outcomes for the MRR and SR

Sr. No.	Response	Optimal condition	Predicted value	Experimental value	CI_{CE}
1	MRR	Ton_3, $Toff_2$, IP_3, WT_3	31.5639	29.6152	29.3884< μ_{MRR} < 3.7394
2	SR	Ton_1, $Toff_3$, WF_1, WT_1	-3.2777	-3.3888	-3.4393 < μ_{SR} < -3.1161

5. Conclusions

This study examines the impact of machining settings on two critical response parameters, SR and MRR, during the WEDM process of the Nimonic-90 super alloy. Taguchi's robust design was used in the planning and execution of the studies.

1. WEDM can effectively machine the Nimonic-90 super alloy because it acknowledges a higher MRR (31.877 mm^2/min) and a lower SR (1.422 µm) while cutting.
2. Ton, Toff, IP, and WT, among others, are significant machining factors for obtaining maximum MRR.
3. Machining parameters like Ton, Toff, WF, and WT are significant variables for obtaining the minimum SR.
4. Ton was found to be the most significant factor for both MRR and SR, with percentage contributions of 74.57 % and 94.96 % respectively at the 95% confidence level.
5. MRR and SR can be predicted in advance with the help of a regression equation. The results of the confirmation trials show that the experimental findings are quite close to the MRR and SR predictions, supporting the findings of the study.

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