Process Optimization of Parameters for Material Removal Rate and Surface Roughness in Wire EDM using Inconel 625 material

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Abstract: ***Wire EDM is the non-convectional machining process which is mainly used for machining very hard and tough material like super alloys. Application of WEDM is mostly found in aerospace, die making industries due to high accuracy and precision work. Inconel is mainly a super alloy which is mixture of nickel and chromium, which has very high melting point and strength. Due to these properties, Inconel is mainly machined by wire EDM. In this report attempt was made to optimize the different process parameters like pulse on time, pulse off time, peak current and wire feed for the surface roughness and material removal rate. Taguchi L9 orthogonal array along with ANOVA is used for optimize the different parameters so that minimum surface roughness and maximum Material Removal rate obtained.***

Index Terms ***-ANOVA, Inconel 625,Optimization, Taguchi Method, Wire EDM.***

1. INTRODUCTION

Inconel 625 is super alloy of nickel and chromium which is mainly used in gas turbine blades, high temperature fasteners, heat exchanger tubing, seals, combustors, steam generators as well as turbocharger rotors and seals due to its superiority mechanical and thermal properties. These super alloys are facing very difficulties for machining with convectional machining due to limitation of temperature developed in machining. To machining these super alloys non convectional machining such as electro chemical machining, electric discharge machining, ultrasonic machining etc. are used because there capability to machine with high accuracy and excellent finishing. Wire EDM is the advancement of EDM in which wire is used as electrode. [1]. WEDM is an electro–thermal machining in which a series of spark is produced between the electrode (wire) and work piece which is submerged in the dielectric fluid. During the discharge period, work material is rapidly melted and vaporized to form a cut on the workpiece which is flushed by the dielectric fluid. Dielectric is used to cooling the cutting zone and to remove the debris from the cutting zone to ready for the next pulse discharge [2]. Electrode wire is made of copper, zinc or brass coated which have good electrical conductivity with diameter of 0.25mm. In wire EDM there is no direct contact between the electrode and workpiece so that there is no mechanical stress development. The schematic diagram of WEDM is shown in figure 1.

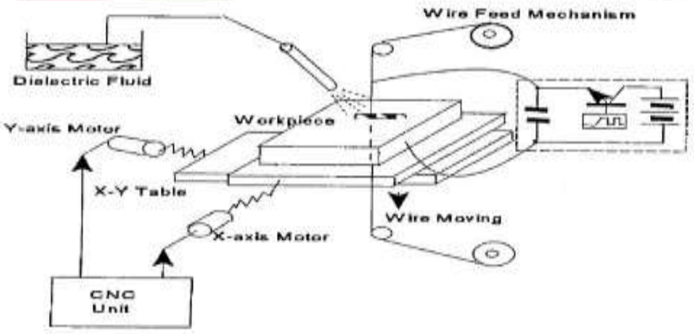

Fig 1. WEDM Mechanism

Several researchers have attempted to optimize the different responses such as MRR, SR and Dimensional deviation. Karsh & Singh made attempt to optimize the different process parameters like pulse on time, pulse off time and peak current for the surface roughness. Taguchi L9 orthogonal array along with ANOVA is used to optimize the different parameters so that minimum surface roughness obtained. They found that pulse on time is the most significant factor [3].Bijaya Bijeta Nayak et al. tried optimization of WEDM process parameters using deep cryo-treated Inconel 718 as work material. This proposed an experimental investigation and optimization of various process parameters during taper cutting of deep cryo-treated Inconel 718 in wire electrical discharge machining process. Taguchi's design of experiment is used to gather information regarding the process with less number of experimental runs considering six input parameters such as part thickness, taper angle, pulse duration, discharge current, wire speed and wire tension. Since traditional Taguchi method fails to optimize multiple performance characteristics, maximum deviation theory is applied to convert multiple performance characteristics into an equivalent single performance characteristic [4].Ugrasen et al. used Taguchi method along with the artificial neural network to optimize the accuracy, surface roughness and MRR. They found that for the above three responses, current is the most significant factor. They used Back propagation feed forward neural network along with Levenberg–Marquardt algorithm to build and train the network [5]. K. Kumar et al. did modelling and optimization of WEDM for surface roughness and MRR in Al-SIC. They used RSM along with Taguchi's L27 OA. They found that factors like speed, feed, Time on and Time off most significant factor for MRR and surface roughness [6]. Antar et al. tried to found the fatigue behavior of Udimet 720 nickel based super alloy by using the minimum damage generator technology in wire EDM. They did comparative study between the wire EDM job and flank milled samples by using S – N curve. They conclude that at the room temperature no significant difference in fatigue life of WEDM and flank milled samples of Udimet 720 alloy [7]. Sharma et al. found the MRR, SR, recast layer, topography, and micro hardness of Inconel 706 for turbine disk application. The proposed experimental plan was based on OFAT approach. The micro hardness and RLT have been examined using the low and high settings of servo voltage and pulse on time. EDAX analysis has been carried out to study the metallurgical changes in the machined surface. They found that pulse on time, pulse off time and servo voltage are most important factors, whereas servo feed is not important. They also found that wire feed of 6 m/min and flushing pressure of 1.96 bar gives higher MRR and SR [8]. Ugrasen et al. in 2014 used Multiple Regression Analysis (MRA), Group Method Data Handling Technique (GMDH) and Artificial Neural Network (ANN) to forecasting effect of process variable on the process response in wire EDM [9]. Md.karimBaig et al. optimize the process parameters of wire EDM for *HastelloyC276* by using the Taguchi and Grey Relational Analysis. MRR and Kerf width are taken as response variable. They found that for MRR and Kerf Width, discharge current (IP) is more important factor. 2 A discharge current is optimum condition for higher MRR and lower Kerf Width. The next parameters that are found to be effective are Servo voltage (SV), Pulse on time (TON), Pulse off time (TOFF) in that order. Grey Relational Analysis (GRA), for finding the optimal parameters affecting both MRR and Kerf are found to be TON = 110 μs, TOFF=60 μs, IP=12A, SV=10 V, for both higher MRR value of 11.78 mm³/min and lower Kerf a value of 0.375 mm [10].

2. EXPERIMENTAL DETAIL

2.1 Theme of Experiment

In this paper an attempt have made to optimize the cutting conditions to minimize the surface roughness and maximize MRR based on the Taguchi method. WEDM involves many process parameters like pulse on time, pulse off time, wire feed, peak current, servo voltage, wire tension, dielectric pressure etc. In this paper only consider first four parameters as mentioned above.

- Pulse on time - The time for which current is applied is called pulse on time, denoted as Ton in micro second (μs).
- Pulse off time - The duration time between the two simultaneous sparks is known as the pulse off time denoted as Toff in (μs). No voltage is applied during this time.
- Peak Current - It is the maximum value of the current passing through the electrodes for the given pulse and represented by IP.
- Wire Feed-Wire feed is the rate at which the wire-electrode travels along the wire guide path and is fed continuously for sparking. The wire feed range available on the present WEDM machine is 1–15 m/min in steps of 1m/min. It is always desirable to set the wire feed to maximum. This will result in less wire breakage, better machining stability and slightly more cutting speed.

2.2 Experimental setup

The experiments were carried out on a wire-cut EDM machine (ELEKTRA ELPU S40) of Electronica Machine Tools Ltd. installed at ABLE TOOLS, Gokul Shirgaon MIDC, Kolhapur, Maharashtra, India. The WEDM machine tool (Figure 2) has the following specifications:

Table 1. WEDM Machine Specification

Design	**Fixed column, moving table**
Table size	440 x 650 mm
Max. workpiece height	200 mm
Max. workpiece weight	500 kg
Main table traverse (X, Y)	300, 400 mm
Auxiliary table traverse (u, v)	80, 80 mm
Wire electrode diameter	0.25 mm (Standard)
	0.15, 0.20 mm (Optional)
Generator	ELPULS-40 A DLX
Controlled axes	X Y, U, V simultaneous /
	Independent

Interpolation	Linear & Circular
Least input increment	0.0001mm
Least command input (X, Y, u, v)	0.0005mm
Input Power supply	3 phase, AC 415 V, 50 Hz
Average power consumption	6 to 7 KVA

Fig. 2 WEDM Machine Tool

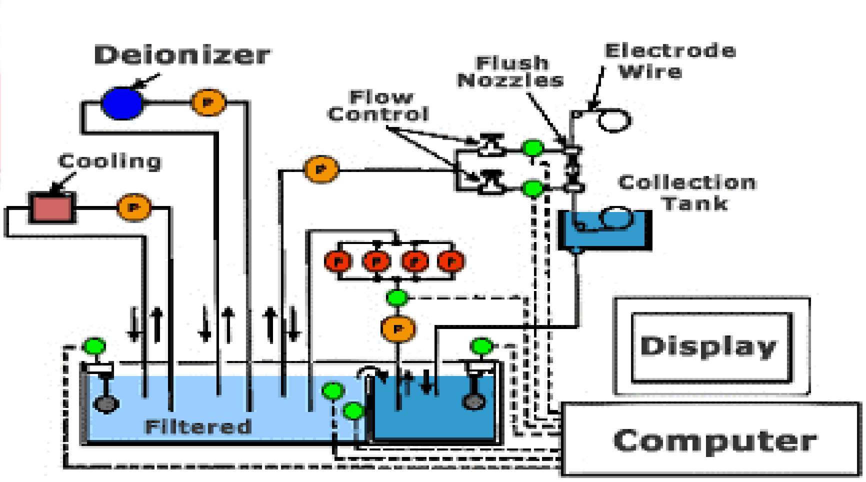

Fig 3. Constructional Details of WEDM Machine Tool

Surface roughness tester is used to measure surface roughness as shown in figure

Fig.4 Set Up for Surface Roughness Measurement

2.3 Experimental design

Taguchi has tabulated 18 basic orthogonal arrays that are known as standard orthogonal arrays. An arrays name indicates the number of rows and columns it has and also number of levels in each of the columns. The number of rows of orthogonal arrays represents number of experiments. In order for an array to be a viable choice, the number of rows must be at least equal to degrees of freedom required for the present study**.**

Table 2. Process Parameters and their Levels

Factors	Parameters	Level		
		L1	L2	L3
A	Pulse on time (µs)	0.6	0.85	1.1
B	Pulse off time (µs)	26	18	14
C	Wire feed (m/min)	2	3	4
D	Peak current(Amp)	120	130	140

For the present experimental work, the four process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behavior of output parameters of study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 2.As we have selected three levels system, Taguchi has suggested L9 orthogonal array which gives nine different experimental combinations. As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has three degrees of freedom (DOF). This gives a total of 8 DOF for four process parameters selected in this work.

2.4 Experimental Results

The Table 3 shows L9 orthogonal array with response values viz. material removal rate and surface roughness obtained after the machining of Inconel 625.

Table 3. Response Values

Sr.No	T On (µs)	T Off (µs)	W F (m/min)	Peak current (amp)	MRR (mm^3/min)	Ra (µ m)
1.	0.6	26	2	120	56.4532	1.908
2.	0.6	18	3	130	60.240	2.130
3.	0.6	14	4	140	56.6757	2.680
4.	0.85	26	4	130	96.969	3.193
5.	0.85	18	2	140	75.6832	2.776
6.	0..85	14	3	120	69.6384	2.630
7.	1.1	26	3	140	94.2092	3.830
8.	1.1	18	4	120	83.2344	3.046

9.	1.1	14	2	130	73.9054	3.250

2.5 Optimization using Grey Relational Analysis

Taguchi's method is focused on the effective application of engineering strategies rather than advanced statistical techniques. The primary goals of Taguchi method are

- A reduction in the variation of a product design to improve quality and lower the loss imparted to society.
- A proper product or process implementation strategy, which can further reduce the level of variation.

The steps involved in Taguchi's Grey Relational Analysis are

Step 1: The transformation of S-N Ratio values from the original response values was the initial step. For that the equations of “larger the better”, “smaller the better” and “nominal the best” were used. Subsequent analysis was carried out on the basis of these S/N ratio values. This is shown in table 4.

$$\text{Type 1: } \frac{S}{N_{HB}} = -10 \log_{10}\left[\left(\frac{1}{N}\right) \left(\sum \frac{1}{Y_{ij}^2}\right) \right] \quad (1)$$

$$\text{Type 2: } \frac{S}{N_{LB}} = -10 \log_{10}\left[\sum \frac{Y_{ij}^2}{n}\right] \quad (2)$$

$$\text{Type 3: } \frac{S}{N_{NB}} = 10 \log_{10}\left[\sum \frac{1}{S^2}\right] \quad (3)$$

Where, Yij is the value of the response“j”in the 1th experiment condition, with i=1, 2, 3, n; j = 1,2…kand S2 are the sample mean and variance.

Table 4. Signal-to-Noise ratios

Sr. No.	Response values		S/N Ratio	
	MRR	Ra	MRR	Ra
1	56.4532	1.908	35.0337	-5.61157
2	60.240	2.130	35.5977	-6.56759
3	56.6757	2.680	35.0678	-8.56270
4	96.969	3.193	39.7327	-10.0840
5	75.6832	2.776	37.5800	-8.86839
6	69.6384	2.630	36.8569	-8.39911
7	94.2092	3.830	39.4818	-11.6640
8	83.2344	3.046	38.4060	-9.67460
9	73.9054	3.250	37.3735	-10.2377

Step 2: In the 2nd step of the grey relational analysis, pre-processing of the data was first performed for normalizing the raw data for analysis. This is shown in Table 7.2. Yij is normalized as Zij (0 ≤ Zij ≤ 1) by the followingformula to avoid the effect of adopting different units and to reduce the variability. The normalized output parameter corresponding to the larger the better criterion and smaller the better can be expressed as

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij}, i=1,2,\ldots n)}{\max(Y_{ij}, i=1,2,\ldots n) - \min(Y_{ij}, i=1,2,\ldots n)} \quad (4)$$

$$Z_{ij} = \frac{\max(Y_{ij}, i=1,2,\ldots n) - Y_{ij}}{\max(Y_{ij}, i=1,2,\ldots n) - \min(Y_{ij}, i=1,2,\ldots n)} \quad (5)$$

Table 5. Normalized Signal-to-Noise ratios

Sr.No	T On	T Off	WF	PC	Normalized S/N Ratio	
					MRR	Ra
1	0.6	26	2	120	1	0
2	0.6	18	3	130	0.879981135	0.157957735
3	0.6	14	4	140	0.992745118	0.487595755
4	0.85	26	4	130	0	0.738947361
5	0.85	18	2	140	0.458124957	0.534998292
6	0..85	14	3	120	0.611998893	0.460568345
7	1.1	26	3	140	0.053376209	1
8	1.1	18	4	120	0.28232947	0.668478435
9	1.1	14	2	130	0.502069192	0.764340369

Step 3: The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized experimental results. Before that the deviation sequence for the reference and comparability sequence were found out. These are given in Table 6 and grey relational coefficient is given in Table 7. The grey relational coefficient can be expressed as

$$\zeta_i(k)=\frac{\Delta_{\min}+\Psi\Delta_{max}}{\Delta_{oi}(K)+\Psi\Delta_{max}} \quad (6)$$

Where, $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence and comparability sequence

$$\Delta_{oi}=||Y_o(k)-Y_i(k)|| \quad (7)$$

$$\Delta_{\min}=\min_{\forall j \in i}\min_{\forall k}||Y_o(k)-Y_i(k)|| \quad (8)$$

$$\Delta_{\max}=\max_{\forall j \in i}\max_{\forall k}||Y_o(k)-Y_i(k)|| \quad (9)$$

$Y_0(k)$ denotes the sequence and $Y_j(k)$ denotes the comparability sequence. Ψ is distinguishing or identified coefficient. The value of Ψ is the smaller and the distinguished ability is the larger. Ψ = 0.5 is generally used.

Table 6. Deviation sequences

Sr. No.	T On	T Off	WF	PC	Deviational Sequence	
					MRR	**Ra**
1	0.6	26	2	120	0	1
2	0.6	18	3	130	0.120018865	0.842042265
3	0.6	14	4	140	0.007254882	0.512404245
4	0.85	26	4	130	1	0.261052639
5	0.85	18	2	140	0.541875043	0.465001708
6	0..85	14	3	120	0.388001107	0.539431655
7	1.1	26	3	140	0.946623791	0
8	1.1	18	4	120	0.71767053	0.331521565
9	1.1	14	2	130	0.497930808	0.235659631

Step 4: The grey relational grade was determined by averaging the grey relational coefficient (GRC) corresponding to each performance characteristic. It is given in the Table 8. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade. The grey relational grade can be expressed as

$$Y_i=\frac{1}{n}\sum_{k=1}^{n}\zeta i(k) \quad (10)$$

Where, γ_i is the grey relational grade for the j^{th} experiment and k is the number of performance characteristics.

Table 7. Grey Relational Co-efficient

Sr. No.	T On	T Off	WF	PC	GRC	
					MRR	**Ra**
1	0.6	26	2	120	1	0.333333333
2	0.6	18	3	130	0.806427075	0.372566508
3	0.6	14	4	140	0.985697757	0.493873867
4	0.85	26	4	130	0.333333333	0.656984779
5	0.85	18	2	140	0.479903999	0.518133798
6	0..85	14	3	120	0.563062361	0.481032108
7	1.1	26	3	140	0.345632364	1
8	1.1	18	4	120	0.410620104	0.601307315
9	1.1	14	2	130	0.501036741	0.679662142

Step 5: Determination of the Optimal Factor and its Level Combination**.** The Table 8 shows the Grey relational grades for maximum MRR, minimum TWR and minimum Ra. Since the experimental design is orthogonal, it is possible to separate out the effect of each machining parameter on the grey relational grade at different levels. The mean of the grey relational grade for each level of the machining parameters is summarized and shown in Table 8.

The larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the machining parameters for the multiple performance characteristics still needs to be known, so that the optimal combinations of the machining parameter levels can be determined more accurately.

Table 8. Grey Relational Grades

Sr.No	T On	T Off	W F	PC	GRG	Rank
1	0.6	26	2	120	0.666666667	3
2	0.6	18	3	130	0.589496792	5
3	**0.6**	**14**	**4**	**140**	**0.739785812**	**1**
4	0.85	26	4	130	0.495159056	9
5	0.85	18	2	140	0.499018899	8
6	0..85	14	3	120	0.522047235	6
7	1.1	26	3	140	0.672816182	2
8	1.1	18	4	120	0.50596371	7
9	1.1	14	2	130	0.590349441	4

With the help of Table 8, we can observe that the parametric combination of number [3] represents highest value of GRG (0.739785812). So, the optimal parameter combination was determined as,

- A1 (pulse on time, 110µs)
- B3 (pulse off time, 40µs)
- C3 (wire feed, 4 m/min)
- D3 (peak current 140)

2.6 Effect of Process Parameters on MRR

Analysis of result presented in above fig. leads to the conclusion that the second level of pulse on time (A2), second level of pulse off time (B2), second level of wire feed (C2), second level of peak current (E4) provide the maximum value of material removal rate (MRR). From the above graphs following conclusions can be drawn:

- S/N ratio for pulse on time increases up to level 2 and further it decreases shortly and increases slowly
- S/N ratio for pulse off time increases continuously
- S/N ratio for wire feed increases continuously
- S/N ratio for peak current increase up to level 2 then slightly decreases.

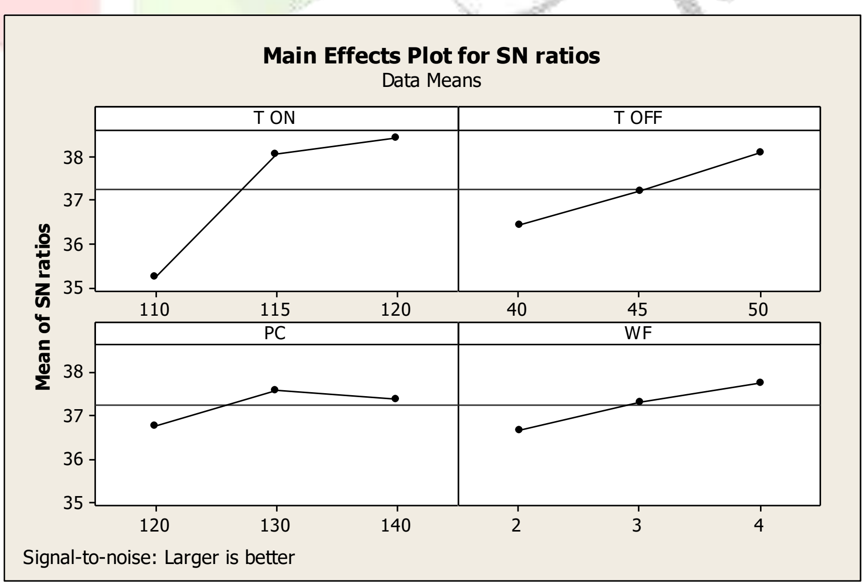

Fig 5. Effect of process parameters on MRR

2.7 Effect of Process Parameters on Ra

Analysis of result presented in above fig. leads to the conclusion that the third level of pulse on time (A3), third level of pulse off time (B3), third level of wire feed (C3), third level of peak current (E3) provides the minimum value of surface roughness. From the above graphs following conclusions can be drawn:

- S/N ratio for Pulse on time decreases slightly for level 2 and level 3.
- S/N ratio for pulse off time increases for level 2 and further it goes on decreasing for level 3
- S/N ratio for wire feed decreases continuously.
- S/N ratio for peak current decreases significantly continuously

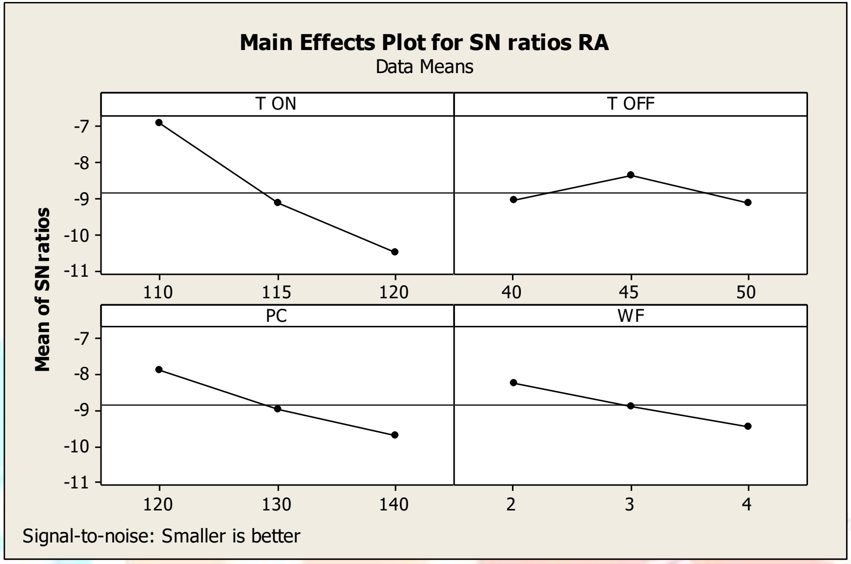

Fig 7. Effect of Process Parameters on Ra

2.8 Prediction Results

Table 9. Predicted and Experimental Values

Description	Optimal Process Parameters		
	Predicted	Experimental	Optimal
Levels	A1 B3 C3 E3	A2 B3 C3 E3	A1 B3 C3 D3
MRR	58.652	57.625	56.657
Ra	1.83	1.75	2.680

The confirmation tests for the optimal parameters with its levels were conducted to evaluate quality characteristics for WEDM of Inconel 625. Table 8 shows highest grey relational grade, indicating the initial process parameter set of A1B3C3D3 for the best multiple performance characteristics among the sixteen experiments. Table 9 shows the comparison of the experimental results for the optimal conditions (A2B3C4D1) with predicted results for parameters (A2B3C3D1).The response values obtained from the experiments are MRR = 5.23 mm^3/min and the Ra = 1.75µm. The comparison again shows the good agreement between the predicted and the experimental values. We can observe from table 9 that the material removal rate increased by 1.10 times and the surface roughness decreased by 0.66 times than the optimal parametric combination. This shows that Taguchi’s method is effective to determine optimal machining parameters with multi-response characteristics of WEDM operations.

2.9Analysis of Variance

Table 10. ANNOVA Results of Process Parameters

Source	DOF	Seq . SS	Adj. SS	Seq.MS	%Contribution
T On	2	1.94271	1.94271	0.97135	70.381923
T Off	2	0.16286	0.16286	0.08143	5.90021
PC	2	0.48703	0.48703	0.24352	17.6444
W F	2	0.16764	0.16764	0.08382	6.0733
Error	0				
Total	8	2.76024	2.76024		

The Analysis of Variance (ANNOVA) shows significant influence of input parameters on the multiple response characteristics of the process.By analyzing the ANNOVA results viz. we doesn't get P-values and F-values for each parameter,due to error zero so we are calculate % contribution by formula it was found that the 'Pulse on time' is the most affecting parameter than other parameters in this process, since it has highest % contribution is (70.3829) and lowest % contribution is (6.0733).The ANNOVA also shows that the parameters 'Pulse off time' and 'Wire feed speed' have moderate effect on the response values, while the parameter 'Wire tension' has the least effect on the response values.

3. Conclusion

The conclusions drawn from above study by GRA for optimization of machining parameters are as follows:

- The optimal combination of machining parameters is:

  Pulse on time = 0.6 µs
  Pulse off time = 14 µs
  Wire feed = 4 m/min
  Peak current = 140 amp

- It was identified that the pulse on time influenced more in the machining operation than other parameters considered in this study.
- The effect of various machining parameter such as pulse on time, wire feed speed, delay time and peak current on the material removal rate and surface roughness were studied while machining of Inconel 625.
- From the present analysis it is evident that the optimal parametric combination will be much more beneficial to the manufacturing communities who are working in the WEDM process.

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