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Optimization of Process Parameters for Wire Cut Electric Discharge Machining of Inconel 718 Super Alloy

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Abstract: The experimental analysis presented aims at the selection of the most optimal machining parameters combination for wire cut electric discharge machining (WEDM) of Inconel 718 super alloy. Based on the Taguchi experimental design (L16 orthogonal array) method, a series of experiments were performed by considering pulse-on time, pulse-off time, peak current and wire tension as input machining parameters. The Material Removal Rate, Surface Roughness and Wire Wear Ratio were considered response variables. The output response variables Material Removal Rate, Surface Roughness and Wire Wear Ratio were calculated and optimized using Single variable Optimization (Taguchi) and Multi Variable Optimization (Taguchi based Grey Relational Analysis) techniques. The ANOVA also carried out to know the percentage contribution of process parameters.

Keywords: Material Removal Rate (MRR), Surface Roughness, Wire Wear Ratio(WWR), Taguchi's L_{16} Orthogonal Array, Taguchi Grey Relational Analysis (TGRA).

I. INTRODUCTION

One of the most widely used Non-Conventional Machining process in industry is Electrical Discharge Machining (EDM). Electric Discharge Machining is a non traditional concept which is based on the principle of removing material by means of repeated electrical discharges between the tool termed as electrode and the work piece in the presence of a dielectric fluid. WEDM is considered as a unique adoption of the conventional EDM process which comprises of a main worktable, wire drive mechanism, a CNC controller, working fluid tank and attachments. The work piece is placed on the fixture table and fixed securely by clamps and bolts. The table moves along X and Y-axis and it is driven by the DC servo motors. Wire electrode usually made of thin copper, brass, molybdenum or tungsten of diameter 0.05-0.20mm, which transforms electrical energy to thermal energy, is used for cutting materials. The wire is stored and wound on a wire drum which can rotate at 1500rpm. The wire is continuously fed from wire drum which moves though the work piece and is supported under tension between a pair of wire guides located at the opposite sides of the work piece. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire, eliminating the mechanical stresses during machining. Also the work piece and the wire electrode(tool) are separated by a thin film of dielectric fluid that is continuously fed to the machining zone to flush away the eroded particles. The movement of table is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece.

II. LITERATURE REVIEW

Amitesh Goswami et.al., investigated on surface integrity, material removal rate and wire wear ratio of Nimonic 80A using WEDM process. The Taguchi's design of experiments methodology has been used for planning and designing the experiments. Pulse-on time (Ton) and pulse-off time (Toff) have been found to be the most significant factors for MRR at 95% significance level, with percent contributions of 46% and 33% respectively. High pulse-on time(Ton) results in faster erosion of the material, as longer duration of spark results in higher spark energy release hence increase in material removal rate. Peak current (IP) and pulse-off time are found to be the major factors affecting the wire wear ratio. Zahid A. Khan et.al., An optimal parameter combination of the WEDM process is obtained using Grey relational analysis. By analyzing the Grey relational grade matrix, the degree of influence for each controllable process factor on to individual quality targets can be found. The pulse ON time is found to be the most influential factor for the surface roughness and the kerf width. Further the results of the analysis of variance (ANOVA) reveals that the Pulse on time is the most significant controlled factor for affecting the multiple responses in the WEDM according to the weighted sum grade of the surface roughness and the kerf width with percentage contribution of 67.13%. The optimal parameter combination obtained from Grey Relational Analysis is Peak Current 3 A, Pulse On Time 15µs and Pulse Off Time 4µs.

III. EXPERIMENTAL METHODOLOGY

A. Taguchi Design Approach

Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical. The original response values are transformed into S/N ratio values. Further analysis is carried out based on these S/N ratio values. The material removal rate is a higher performance characteristics, since the maximization of the quality characteristic of interest is sought and can be expressed as

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (1)$$

The surface roughness and wire wear ratio is the lower-the performance characteristic and the loss function for the same can be expressed as

$$S/N = -10\log_{10}\left(\frac{\sum y^2}{N}\right) \quad (2)$$

B. Taguchi Grey Relational Analysis (TGRA)

In the GRA, experiment data, i.e., measured responses are first normalized in the range of 0 to 1. This process is called normalization. Based on this data, grey relation coefficients are calculated to represent the correlation between the ideal (best) and the actual normalized experimental data. Overall, grey relation grade is then determined by averaging the grey relation coefficient corresponding to selected responses. The overall quality characteristics of the multi-response process depend on the calculated grey relation grade. Here, Taguchi based Grey Relational Analysis (TGRA) is used. How it is differ from normal GRA is, GRA has to be apply to S/N ratios of results of response variables instead means of response variables.

Normalization: There are three different types of data normalization according to the requirement of Lower the Better (LB), Higher the Better (HB), or Nominal the Best (NB) criteria. If the target value of original sequence is infinite, then it has a characteristic of the "higher is better". The original sequence can be normalized as follows:

$$x_i^* = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (3)$$

When the "Smaller is better" is a characteristic of the original sequence, then the original sequence should be normalized as follows:

$$x_i^* = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (4)$$

Where i = 1 . . . m; k = 1. . . n. m is the number of experimental data items and n is the number of parameters. $X_i^0(k)$ denotes the original sequence, x_i^* the sequence after the data pre-processing, max $x_i^0(k)$ the largest value of $x_i^0(k)$, min $x_i^0(k)$ the smallest value of $x_i^0(k)$ and x^0 is the desired value. The deviation sequence, $\Delta_{0i}(k)$ is the absolute difference between the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$ after normalization. It is determined using equation: $\Delta_{0i} = \|x_0^*(k) - x_i^*(k)\|$.

Calculation of Grey Relational Coefficient (GRC): GRC for all the sequences expresses the relationship between the ideal (best) and actual normalized S/N ratio. If the two sequences agree at all points, then their grey relational coefficient is 1. The grey relational coefficient ξi(k) for the kth performance characteristics in the ith experiment can be expressed as :

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \quad (5)$$

Where Δ_{0i} is the deviation sequence of the reference sequence and $x_0^*(k)$ is the comparability sequence. ζ is distinguishing or identification coefficient: ζ □ [0, 1] (the value may be adjusted based on the actual system requirements). A value of ζ is the smaller and the distinguished ability is the larger. ζ = 0.5 is generally used and where

$$\Delta_{min} = \min_{\forall j \in i}\min_{\forall k}\|x_0^*(k) - x_i^*(k)\| \quad (6)$$

$$\Delta_{max} = \max_{\forall j \in i}\max_{\forall k}\|x_0^*(k) - x_i^*(k)\| \quad (7)$$

Calculate Grey relational coefficient for 16 comparability sequences by using above formulas.

Calculation of Grey Relational Grade (GRG): After the grey relational coefficient is derived, it is usual to take the average value of the grey relational coefficients as the grey relational grade. The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (8)$$

The grey relational grade γi represents the level of correlation between the reference sequence and the comparability sequence. If the two sequences are identical, then the value of grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades.

ANOVA: Analysis of Variance (ANOVA) is a statistical method for determining the existence of differences among several population means. The aim of ANOVA is the detect differences among several population means, the technique requires the analysis of different forms of variance associated with the random samples under study.

IV. EXPERIMENTATION

The material selected for this dissertation work is Inconel 718 alloy. Its chemical composition is given in table 1 and Selection of levels of Process Parameters as shown in table 2.

TABLE I: Chemical Composition of Inconel 718

Element	C	Mn	Si	Ti	Al	Co	Mb	Cb	Fe	Cr	Ni
Percentage(%)	0.08	0.35	0.35	0.6	0.8	1.0	3.0	5.0	17.0	19.0	52.82

TABLE II : Process Parameters and Their Levels

Symbol	Input Parameter	Level 1	Level 2	Level 3	Level 4
T_{on}	Pulse on time(µs)	122	124	126	128
T_{off}	Pulse off time(µs)	52	54	56	60
IP	Peak Current(A)	170	190	210	230
WT	Wire Tension(g)	3	5	7	9

The experiments are conducted on the Electronic Sprint Cut Wire Electrical Discharge Machine. The wire selected for machining is Brass of 0.25mm diameter. The following steps are followed in the cutting operation as shown in Fig.1. Work piece material with dimensions length 50mmx25mmx8mm is to be prepared in the lathe for all the 16sets of experiments.

Fig.1. Work pieces and Wire after machining.

Measurement of the surface roughness was founded using the mitutoyo sj-201p and material removal rate and wire wear ratio has been calculated by the following formula

$$\text{MRR} = \frac{Wi-Wf}{\rho * t}\ mm^3/\text{min} \quad , \text{WWR} = \frac{Wi-Wf}{Wi} \qquad \textbf{(9)}$$

V. RESULTS AND DISCUSSIONS

TABLE III: Experimental results and S/N ratios for Material Removal Rate, Surface Roughness and Wire Wear Ratio

Exp. No	T_{ON} (µs)	T_{OFF} (µs)	IP (A)	WT (g)	MRR (mm^3/min)	S/N ratio	SR (µm)	S/N ratio	WWR	S/N ratio
1	122	52	170	3	1.73216	4.77176	1.576	-3.95112	0.0751	22.4872
2	122	54	190	5	2.267	7.10903	1.814	-5.17275	0.0910	20.8192
3	122	56	210	7	3.1097	9.85437	1.475	-3.37584	0.0933	20.6024
4	122	60	230	9	4.2172	12.50048	1.532	-3.70518	0.1448	16.7846
5	124	52	190	7	1.89736	5.562995	1.63	-4.24375	0.1027	19.7686
6	124	54	170	9	3.0189	9.596975	1.48	-3.40523	0.1093	19.2276
7	124	56	230	3	2.285	7.177724	1.845	-5.31993	0.0793	22.0145
8	124	60	210	5	3.237	10.20285	1.39	-2.8603	0.0907	20.8479
9	126	52	210	9	4.7504	13.5346	2.188	-6.80095	0.1053	19.5514
10	126	54	230	7	5.58634	14.94255	2.032	-6.15847	0.1043	19.6343
11	126	56	170	5	1.87564	5.46299	1.532	-3.70518	0.0880	21.1103
12	126	60	190	3	4.44	12.94766	1.22	-1.7272	0.0810	21.8303
13	128	52	230	5	6.7325	16.56353	2.22	-6.92706	0.0955	20.3999
14	128	54	210	3	5.63138	15.0123	1.758	-4.90038	0.0833	21.5871
15	128	56	190	9	3.3768	10.57011	1.35	-2.60668	0.1160	18.7108
16	128	60	170	7	3.8033	11.60321	1.382	-2.81016	0.0907	20.8479

By using the software MINITAB 17 the Taguchi Analysis was performed. The means and S/N ratios of response variables are generated and their behaviour for process parameters as shown below fig.2, 3 and 4

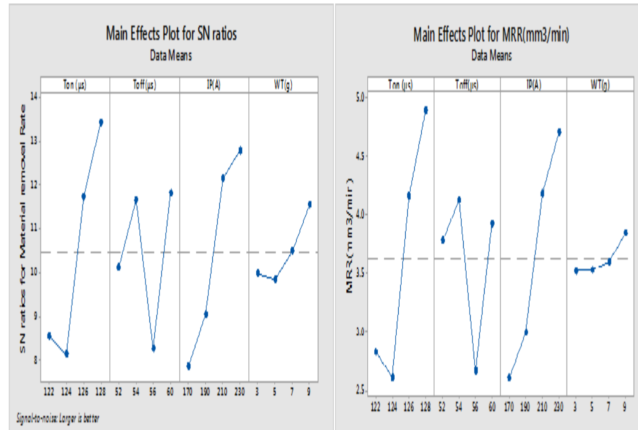

Fig.2.Graph of Input Parameters v/s MRR.

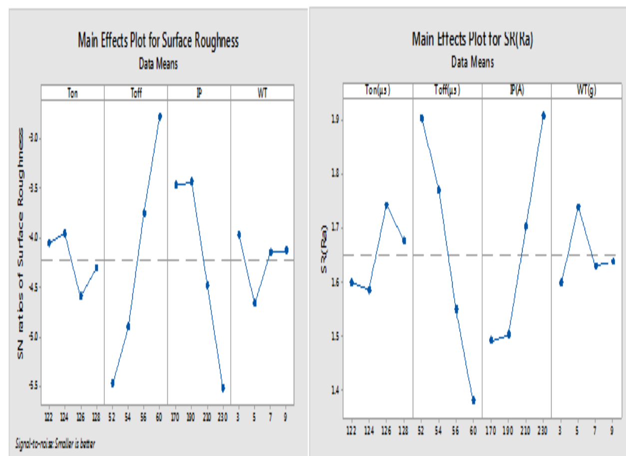

Fig.3.Graph of Input Parameters v/s SR.

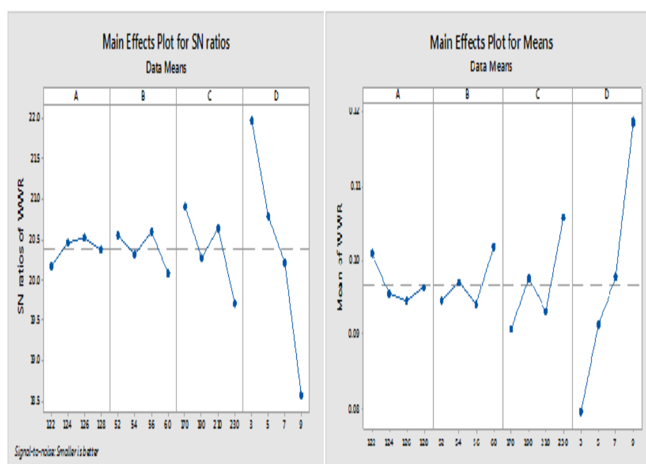

Fig.4. Graph of Input Parameters v/s WWR.

At the optimal parameter levels for Material Removal Rate, Surface Roughness, Wire Wear Ratio which were obtained from Taguchi Analysis the values are predicted and confirmation tests was done.

TABLE IV: Results for Grey Relational Analysis

Exp. No	COMPARIBILITY SEQUENCES(for S/N ratios)			DEVIATION SEQUENCES			GREY RELATIONAL COEFFICINT			GRADE	RANK
	MRR	SR	WWR	MRR	SR	WWR	MRR	SR	WWR		
1	0	0.427	0	1	0.573	1	0.32	0.4202	0.3143	0.3515	15
2	0.198	0.6626	0.2924	0.802	0.3974	0.7075	0.3698	0.5110	0.3932	0.4246	11
3	0.431	0.3170	0.3305	0.569	0.6829	0.6694	0.4527	0.3782	0.4065	0.4125	12
4	0.6554	0.38039	1	0.3446	0.6196	0	0.5775	0.4013	1	0.6596	5
5	0.0671	0.48396	0.4767	0.9329	0.5160	0.5233	0.3354	0.4459	0.4670	0.3334	16
6	0.4092	0.3227	0.5715	0.5908	0.6773	0.4284	0.4434	0.3801	0.5169	0.4468	8
7	0.204	0.6909	0.0828	0.796	0.3091	0.9171	0.3715	0.5733	0.3334	0.4261	10
8	0.4605	0.2171	0.2874	0.5399	0.7821	0.7126	0.4657	0.3469	0.3915	0.4014	13
9	0.743	0.9757	0.5148	0.257	0.0242	0.4851	0.6468	0.944	0.4855	0.690	3
10	0.8625	0.8521	0.5002	0.1375	0.1478	0.4997	0.7739	0.7375	0.4785	0.6633	4
11	0.0586	0.3803	0.2412	0.9414	0.6196	0.7586	0.3334	0.4013	0.3767	0.3705	14
12	0.6933	0	0.1151	0.1306	1	0.8848	0.6054	0.2935	1.8019	0.9002	1
13	1	1	0.3660	0	0	0.6339	1	1	0.4197	0.8065	2
14	0.8684	0.6102	0.1578	0.1315	0.3897	0.8421	0.7815	0.5159	0.3525	0.5499	6
15	0.4917	0.1691	0.6622	0.5083	0.8308	0.3378	0.4807	0.3334	0.5758	0.4633	7
16	0.5793	0.2082	0.2874	0.4206	0.6791	0.7126	0.528	0.3795	0.3915	0.4330	9

At the optimal parameter levels for Grey Relational Grade obtained from Taguchi Analysis the MRR, SR and WWR values are predicted and confirmation test was done.

A. Predicted results and Confirmation Test results obtained from Taguchi and Taguchi Grey Relational Analysis

From the Taguchi Analysis optimal parameter level for MRR is Pulse on time is 128µs, Pulse off time is 60 µs, Peak current 230 A, Wire Tension is 9gm and at this level the experimental value of MRR is found to be 6.21 mm^3 /min. While the optimal parameter level obtained for surface Roughness is Pulse on time is 126µs, Pulse off time is 60 µs, Peak current 190 A, Wire Tension is 3 g and at this level the experimental value of Surface Roughness is found to be 0.985µm. While the optimal parameter level obtained for Wire Wear Ratio is Pulse on time is 126 µs, Pulse off time is 56 µs, Peak current 170 A, Wire Tension is 3 g and at this level the experimental value of Wire Wear Ratio is found to be 0.0632.

TABLE V: Results Obtained for Taguchi Analysis

Optimization		Optimum Level	Predicted	Confirmation Test
Taguchi Analysis of Design	Material Removal Rate	Ton_{L4} =128 μs $Toff_{L4}$ = 60 μs IP_{L4} = 230 A WT_{L4} = 9 g	6.48856 mm^3/min	6.21mm^3/min
	Surface Roughness	Ton_{L3} = 126µs $Toff_{L4}$ = 60 µs IP_{L2} =190 A WT_{L1} =3 g	1.116 µm	0.985 µm
	Wire Wear Ratio	Ton_{L3} =126 µs $Toff_{L3}$ = 56 µs IP_{L1} = 170 A WT_{L1} = 3 g	0.06857	0.0632

TABLE VI: Results obtained for Taguchi Grey Relational Analysis

Optimization	Predicted Grey Relational Grade	Optimal Level Of Parameters	Confirmation Test For		
			Material Removal Rate	Surface Roughness	Wire Wear Ratio
Taguchi Grey Relational Analysis	0.8954	Ton_{L3}=126 µs $Toff_{L4}$ = 60µs IP_{L4} = 230 A WT_{L4} = 9 g	7.1 mm^3/min	0.86 µm	0.0559

From the Taguchi based Grey Relational Analysis, it was found that the optimal parameter level is Pulse on time 126µs, Pulse off time 60µs, Peak current 270A, Wire Tension 3g. The confirmation test was carried out at this level then observed the following results: Material Removal Rate 7.1mm^3/min, Surface Roughness 0.86µm, Wire Wear Ratio 0.0559. Tables 5 and 6 shows the comparison of the experimental results using the Taguchi and Taguchi Grey Relational Analysis. We can observe Material Removal Rate is increased from 6.63 to 7.1 mm^3/min, the is Surface Roughness decreased from 0.985 to 0.86 µs and the Wire Wear Ratio is also decreased from 0.0632 to 0.0559 for Taguchi based Grey Relational Analysis. The corresponding improvements in Material Removal Rate , Surface Roughness and Wire Wear Ratio 14.33 %, 12.35 % and 11.55% respectively. It is clearly shown that by applying Multi variable Optimization for process parameters optimization in WEDM, greatly improved the output Response Variables.

B. ANOVA Analysis

TABLE VII: ANOVA for Material Removal Rate

	Means					S/N ratios				
Source	DF	SS	MS	F	% of contribution	DF	SS	MS	F	% of contribution
T_{on}	3	14.16	4.72	2.86	41.7	3	77.9	25.97	2.48	38.2
T_{off}	3	5.167	1.722	0.72	15.21	3	32.88	10.96	0.77	16.1
IP	3	11.64	3.879	2.09	34.28	3	68.31	22.77	2.02	33.5
WT	3	0.2688	0.08961	0.03	0.7916	3	7.257	2.419	0.5	3.6
Residual Error	3	2.7142			8.018	3				8.5
Total	15	33.95			100	15				100

TABLE VIII: ANOVA for Surface Roughness

	Means					S/N ratios				
Source	DF	SS	MS	F	% of contribution	DF	SS	MS	F	% of contribution
T_{on}	3	0.06414	0.02138	0.2	4.77	3	0.9931	0.3310	0.12	2.4
T_{off}	3	0.6446	0.21487	3.68	47.94	3	17.48	5.826	4.00	50.3
IP	3	0.4609	0.15363	2.09	34.2	3	11.83	3.943	2.05	34.6
WT	3	0.04401	0.01467	0.14	3.27	3	1.09	0.3634	0.13	3
Residual Error	3	0.13074			9.82	3	3.567			10.3
Total	15	1.34439			100	15	34.96			100

TABLE IX: ANOVA for Wire Wear Ratio

	Means					S/N ratios				
Source	DF	SS	MS	F	% of contribution	DF	SS	MS	F	% of contribution
T_{on}	3	0.00009	0.00033	0.09	2.22	3	0.2903	0.0967	0.04	0.95
T_{off}	3	0.00014	0.000049	0.14	3.34	3	0.7090	0.2363	0.10	2.3
IP	3	0.00053	0.000179	0.56	12.22	3	3.286	1.095	0.48	10.7
WT	3	0.00324	0.001081	11.2	73.6	3	24.158	8.0527	15.1	79.14
Residua l Error	3	0.00037			8.61	3	2.099			6.9
Total	15	0.00440			100	15	30.5423			100

VI. CONCLUSIONS

From Taguchi Analysis:

- The material removal rate was found to be 6.21mm^3/min at optimal parameter levels of Pulse on time at level 4(128µs), Pulse off time at level 4(60µs), Peak Current at level 4(230A), Wire Tension at level 1(3gms).
- The Surface Roughness was found to be 0.985µm at optimal parameter levels of Pulse on time at level 3(126 µs), Pulse off time at level 4 (60µs), Peak Current at level 1(170A), Wire Tension at level 1(3gms).
- The Wire Wear Rate was found to be 0.06857 at optimal parameter levels of Pulse on time at level 3(126 µs), Pulse off time at level 3(56µs), Peak Current at level 2(190A), Wire Tension at level 1(3gms).

From Taguchi Grey Relational Analysis(TGRA):

- The material removal rate was 7.1mm^3/min, Surface Roughness was 0.86µm and Wire Wear Ratio was 0.0559 at optimal parameter level Pulse on time at level 3(126 µs), Pulse off time at level 4 (60µs), Peak Current at level 4(230A), Wire Tension at level 4(9gms).
- The response variables Material Removal rate, Surface Roughness and Wire Wear Ratio are greatly improved by Grey Relational Analysis compared to Taguchi.

From ANOVA:

- Pulse on time and Peak Current are the most influential parameters in increase of Material Removal Rate.
- Pulse off time and Peak Current are the most influential parameters in decrease of Surface Roughness.
- Wire Tension is the most influential parameter in decrease of Wire Wear Ratio.

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