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OPTIMIZATION OF PROCESS PARAMETER IN WEDM FOR MONEL K-500 USING TAGUCHI AND GRA

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Abstract

Wire Electrical Discharge machining process is extensively used in mechanical industry to manufacture geometrically complex, intricate shape and very hard material parts that are extremely difficult to machine by conventional machining process. The objective of the present work is to investigate the effects of the various WEDM process parameters like pulse on time (T_{ON}), pulse off time (T_{OFF}), peak current (IP), Servo voltage (SV) on material removal rate(MRR) and surface roughness (SR) of Monel K-500 by using Ultima-1F wire-cut EDM machine.The experimentation has been done by using Taguchi'^s^ L_{27} Orthogonal Array. Multi response optimization method using grey relation analysis is proposed for optimization of parameters.

Keywords: WEDM, Material removal rate, Surface roughness, GRA.

1. Introduction

In mechanical industry, the demands for alloy materials having high hardness, toughness and impact resistance are increasing. These materials are difficult to be machined by traditional machining methods. To satisfy the present demands of the manufacturing industries, a different class of modern machining techniques such as Wire Electrical Discharge Machining (WEDM) have emerged. Which is the best alternative for the production of small scale complex parts with the highest degree of surface finish and dimensional accuracy.

Wire EDM machining (Electrical Discharge Machining) is an electro thermal production process, which erodes and vaporize material from the surface of workpiece by using a series of discrete spark between workpiece andtool electrode separated by dielectric fluid.

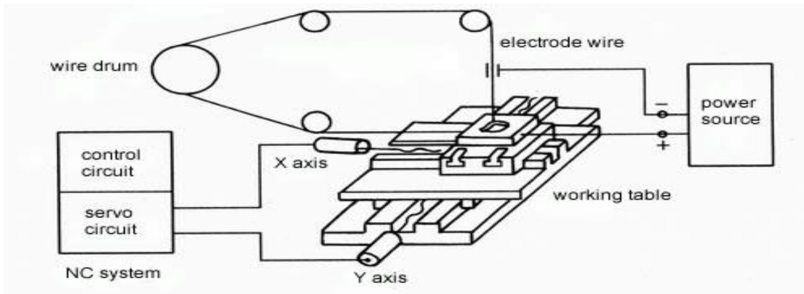

Figure1: Set up of Electric discharge machining

This fluid acts as cooling agent and it also flushes away the eroded particles from the work zone. WEDM utilizes a continuously traveling single stranded wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.3 mm, against workpiece through CNC wire guide[2]. Fig.1 is shows the setup of the Electric discharge machining. Proper gap is maintained between wire and workpiece,when the voltage across the gap becomes sufficiently high spark occurs and pressure developed between work and tool. As a result of which a very high temperature is reached and at such high pressure and temperature that some metal is melted and eroded. Such localized extreme rise in temperature leads to material removal. Wire electrical discharge machining is complex, time varying stochastic process in which output of machine depends on input variables. To harness the full potential of WEDM machine toolit is priority to run the machine with optimum parameters. Many researchers have been contributed their efforts towards optimization cutting parameters.**Tosunet at. [2004]** studied the influence of open circuit voltage, pulse duration, wire speed, flushing pressure on kerf and metal removal rate on a Sodick A320D/EX21 WEDM machine tool with AISI 4140 steel(with 200mm × 40mm × 10mm) with CuZn37 Master brass wire of 0.25mm diameter. L_{18} orthogonal array was used. ANOVA shows that open circuit voltage and pulse duration were highly effective parameters on both the kerf and the MRR whereas wire speed and dielectric flushing pressure were less effective factors.**Mahapatra et al. [2006]** conducted experiment to study various significant control factors which effect the machining performance on Robofil 100 high precision five axis CNC WEDM using Zinc coated copper wire with 0.25 mm diameter and a block of D2 tool steel as work piece material. TAGUCHI method was used for experiment. The results of confirmation experiment agree well with the predicted optimal settings as an error of 4.062 % in MRR and 1.53 % SF and discharge current, pulse duration, pulse frequency play significant role in finish cutting operation was observed.**Mahapatra et al. (2007)** established a relationship between control factors and responses like MRR, SF and kerf by means of nonlinear regression analysis, resulting in a valid mathematical model. Genetic algorithm was employed to optimize the wire electrical discharge machining process with multiple objectives. Experiments were performed on ROBOFIL 100 high precision 5-axis CNC WEDM as per Taguchi method (L_{27} OA) using D2 tool steel specimen of 200mm×25mm×10mm. The confirmation experiment shows that the errors associated with MRR, SF, and kerf are 3.14, 1.95, and 3.72%, respectively**Ramakrishnan et al. [2008]** studied the influence of pulse on time, delay time, wire feed speed, and ignition current on metal removal rate and surface roughness of Inconel 718 material of thickness 20mm on five-axis Robofil 290P CNC WEDM. Experiments were planned as per Taguchi's L_9 orthogonal array. Artificial neural network (ANN) models and multi response optimization technique was used to predict and select the best cutting parameters of WEDM. ANOVA was employed to identify the level of importance of the machining parameters. Experimental result shows that the developed ANN models could predict the performance characteristics of WEDM process more accurately and the pulse on time, delay time and ignition current influenced more than wire feed speed on the performance characteristics. **H.Singh et al. (2009)** studied the effects of various process parameters of WEDM like pulse on time

(T_{ON}), pulse off time (T_{OFF}), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) to reveal their impact on material removal rate of hot die steel (H-11) using one variable at a time approach on Electronica sprint cut WEDM machine. Results show that the material removal rate (MRR) directly increases with increase in pulse on time (T_{ON}) and peak current (IP) while decreases with increase in pulse off time (TO_{FF}) and servo voltage (SV).**Jangra et al. [2011]** investigated the influence of taper angle, peak current, pulse-on time, pulse-off time, wire tension and dielectric flow rate to optimize MRR and SR simultaneously on 5-axis sprint cut ELPLUS-40 WEDM machine made by Electronica with WC-Co composite material. Taguchi's L_{18} orthogonal array was used for the experimentation. GRA was used for the optimization of process parameters and ANOVA was used to show the most significant parameters affecting the multiple machining characteristics. The experimental setup showed that taper angle, pulse-on time and pulse-off time were found the most significant affecting the MRR and SR.**Jaganathanet al. [2012]** evaluatedthe influence of applied voltage, Pulse width, Pulse interval and speed on MRR. Experiment was performed on ST CNC-E3 (MCJ) WEDM machine with E 31 material. Taguchi's Mixed L_{27} orthogonal array and DOE was used**.** The experimentation setup resulted that applied voltage, Pulse width speed was most significant factors. **Kulkarni et al. [2014]** studied the influence of various process parameters such as pulse on time, pulse off time, wire feed, wire tension, upper flush and lower flush on MRR and SR for high carbon high chromium steel using Electronica maxicut 734 CNC Wire-cut electrical discharge machining (WEDM). Taguchi's L_{25} Orthogonal Array along with utility concept was used to optimize the response characteristics such as Material removal rate, surface finish and kerf width. Shows that the order of influencing parameters for MRR was pulse-off time, upper flush, lower flush and wire tension and for SR was pulse-on time, Lower Flush, Wire Feed, Wire tension.

2. Methodology

In the present work, Taguchi method using L_{27}orthogonal arrays (Table 4) has been employed for the design of experiments. The various control factors along with their symbols shown in Table 1. Pulse on time, pulse off time, peak current and servo voltage are set as control factors (independent variable) which vary during the experiment. With the help of machine manual, many trail experiments were done to determine the operating range of each factor finally selected.The Taguchi method tests pairs of combinations instead of testing all possible combinations. From the available literature on WEDM, total four numbers of input parameters were finally selected and range of levels of control factors is shown in Table 2.

In this present research work, orthogonal array with four control factors viz., A, B, C, D, and three interactions viz. A× B, A×C have been studied. Signal to noise ratio was obtained using Minitab 16 software. Higher is better (HB) for MRR and lower is better (LB) for SR were taken for obtaining optimum machining characteristics.

Table 1: Process parameters and their symbols

Control factor(Symbol)	Parameter kept constant
Pulse on time (A)	Wire tension = 8
Pulse off time (B)	Wire feed = 8
Peak current (C)	Servo Feed- 2050 mm/min
Servo voltage (D)	Dielectric flow rate = 10

Table 2: Levels for various control factors

Control factor	Symbol	Level		
		Level 1	**Level 2**	**Level 3**
Pulse on time	A	110	115	120
Pulse off time	B	50	55	60
Peak current	C	11	12	13
Servo voltage	D	40	50	60

Table 4: Taguchi's L_{27} Standard Orthogonal Array

Column no	1	2	3	4	5	6	7	8	RESPONSE RAW DATA			S/N RATIO
Trial no.	**A**	**B**	**A×B**	**A×B**	**C**	**A×C**	**A×C**	**D**	**R1**	**R2**	**R3**	
1	1	1	1	1	1	1	1	1	$Y1_1$	$Y1_2$	$Y1_3$	S/N(1)
2	1	1	1	1	2	2	2	2	.	.	.	.
3	1	1	1	1	3	3	3	3	.	.	.	.
4	1	2	2	2	1	1	1	2	.	.	.	.
5	1	2	2	2	2	2	2	3	.	.	.	.
6	1	2	2	2	3	3	3	1	.	.	.	.
7	1	3	3	3	1	1	1	3	.	.	.	.
8	1	3	3	3	2	2	2	1	.	.	.	.
9	1	3	3	3	3	3	3	2	.	.	.	.
10	2	1	2	3	1	2	3	1	.		.	.
11	2	1	2	3	2	3	1	2	.	.	.	.
12	2	1	2	3	3	1	2	3	.	.	.	.
13	2	2	3	1	1	2	3	2	.	.	.	.
14	2	2	3	1	2	3	1	3	.	.	.	.
15	2	2	3	1	3	1	2	1	.	.	.	.
16	2	3	1	2	1	2	3	3	.	.	.	.
17	2	3	1	2	2	3	1	1	.	.	.	.
18	2	3	1	2	3	1	2	2	.	.	.	.
19	3	1	3	2	1	3	2	1	.	.	.	.
20	3	1	3	2	2	1	3	2	.	.	.	.
21	3	1	3	2	3	2	1	3	.	.	.	.
22	3	2	1	3	1	3	2	2	.	.	.	.
23	3	2	1	3	2	1	3	3	.	.	.	.
24	3	2	1	3	3	2	1	1	.	.	.	.
25	3	3	2	1	1	3	2	3	.	.	.	.
26	3	3	2	1	2	1	3	1	.	.	.	.
27	3	3	2	1	3	2	1	2	$Y27_1$	$Y27_2$	$Y27_3$	S/N(27)

3. Experimental set up

The experiments were performed on Ultima-1F wire-cut EDM machine of Electronica Machine tools Ltd. The Monel k-500 (Nickel 63.0%,Copper 27.0%-23.0%,Iron 2.0%, Titanium0.35%-0.85%) plate of 100mm x 100mm x 19.85mm size is mounted on machine tool fig.2. Table 3 shows the limiting chemical composition of Monel K-500. In the present research work Mitutoyosurfest SJ- 210 instrument (fig. 3) is used for the measurement of Surface Roughness of the specimen.This (Mitutoyosurfest SJ- 210) is shop- floor type surface roughness measuring instrument.Mitutoyosurfest SJ-210 traces the surface of various machine part and calculate the surface roughness based on roughness standard and display the results.

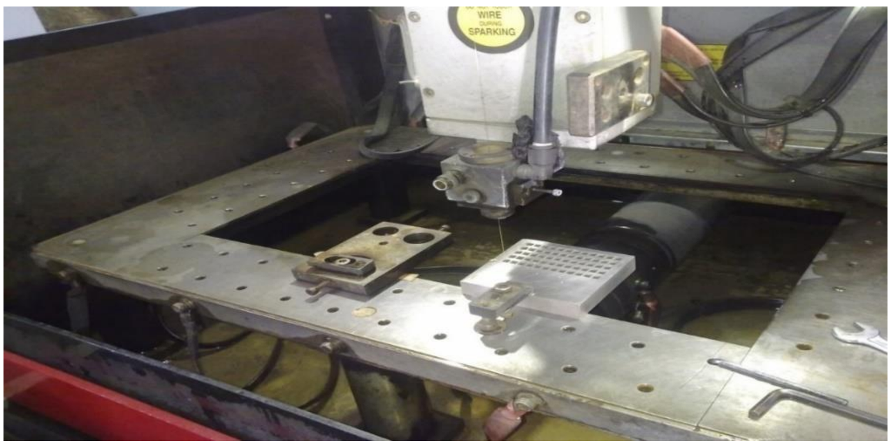

Figure 2: Monel K- 500 Plate Mounted on WEDM Machine

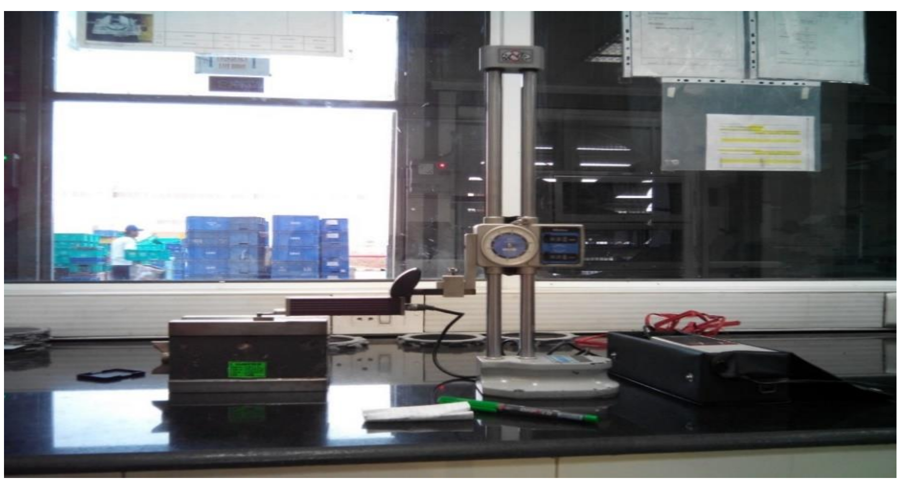

Fig. 3: MitutoyoSurftest SJ-210 (Surface RoughnessTester)

Table 3: Limiting Chemical Composition, %

Nickel	63.0 min
Copper	27.0-23.0
Iron	2.0 max
Sulfur	0.01 max
Carbon	0.25max
Manganese	1.5max
Silicon	0.5 max
Sulfur	0.01 max
Aluminum	2.3-3.5 max
Titanium	0.35-0.85

Digital stop watch was used to calculate the time taken by machine to cut the particular specimen. Material removal rate is measure of material removal from workpiece which is quantitatively given as mm^2/min and is calculated as:

MRR = [Distance travelled by wire (mm) x Thickness of workpiece (mm)]/Time (min.)] (1)

4. Single response optimization

The Taguchi approach has been used for predicting the confidence intervals for the predicted mean has been applied. Three Confirmation experiments for each performance characteristics have been performed at optimal settings of the process parameters and the average value has been reported. The optimum value of material removal Rate (MRR) is predicted at the optimal levels of significant variables which have already been selected as pulse on time (A3), pulse off time (B1), peak current (C3) and spark gap set voltage (D1) shown in table fig.4 and experimental results of MRR and SR are shown in Table no.5.Predicted Optimal Values, Confidence Intervals and Results of Confirmation experiments are shown in Table 8. The estimated mean of the response characteristic (MRR) can be determined [8] as:-

$$\mu_{MRR} = \{(A3 + B1 + C3 + D1) - 3(\mu)\}$$
$$= \{(48.56+47.16+46.98+45.89)-3(39.641)\}$$
$$= 188.59 - 118.923$$
$$= 69.67 mm^2/min$$

The 95 % confidence intervals of confirmation experiments (CI_{CE}) is calculated as:

$$CI_{CE} = \sqrt{F_{\alpha}(1 \cdot f_e)\left\{\frac{1}{n_{eff}} + \frac{1}{R}\right\} V_e} = 1.830$$

Where, $F_{\propto}(1, f_e)$ = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e = 3.99 (from Tabulated F value)

$$n_{eff} = \frac{N}{1 + \text{Total DF involved in estimation of mean}}$$

$$= 81 / (1+8)$$

= 9

N = Total number of results = 27 x 3 = 81

R = Sample size for confirmation experiments = 3

Ve = Error variance = 1.89,fe = error DOF = 64 (Table 6)

Therefore, the predicted confidence interval for confirmation experiments is:-

$\mu_{MRR} - CI_{CE} < \mu_{MRR} < \mu_{MRR} + CI_{CE}$

$67.84 < \mu_{MRR} < 71.50$

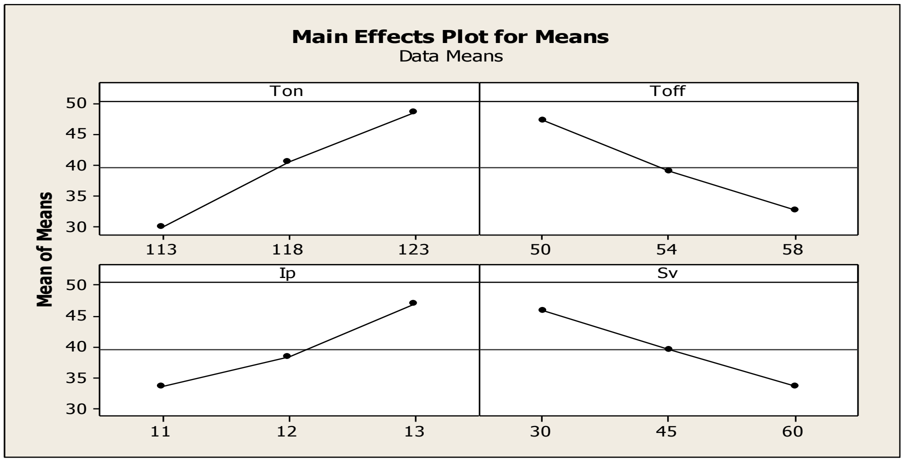

Figure 4: Main Effect Plot for Means (for Material Removal Rate)

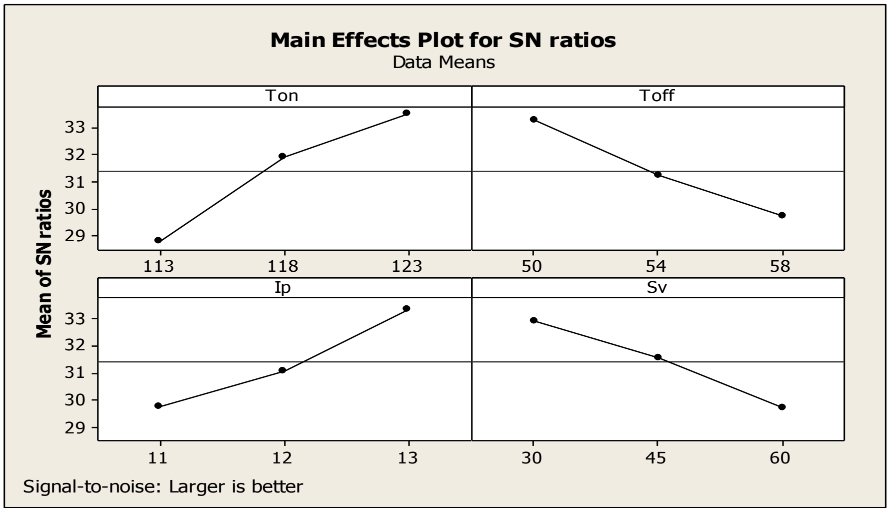

Figure 5: Main Effect Plot for S/N ratio (for Material Removal Rate)

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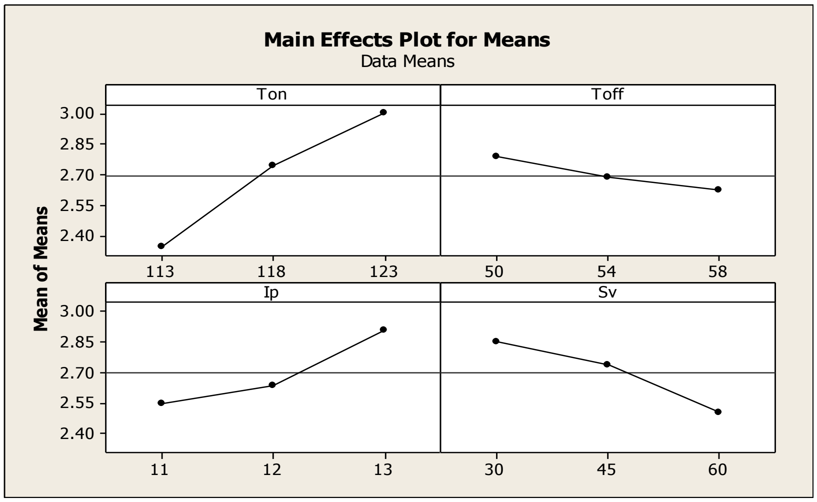

Figure 6: Main Effect Plot for Means (Surface Roughness)

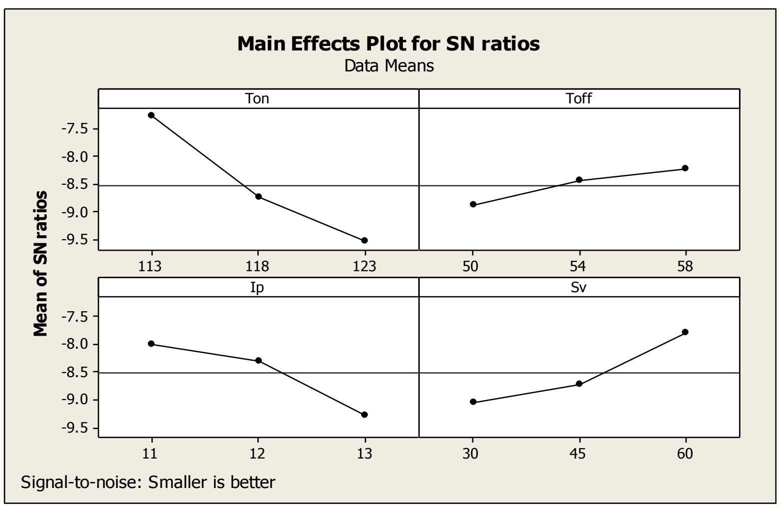

Figure 7: Main Effect Plot of Surface Roughness (S/N ratio)

Similarly for Surface Roughness (SR):

μ_{SR} = {(A1 + B3 + C1 + D3) - 3(μ)}

= {(2.345+2.621+2.547+2.504)-3(2.697)}

= 10.017 – 8.091

= 1.926μm

Where,

The 95 % confidence intervals of confirmation experiments (CI_{CE}) are calculated as:-

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)\left\{\frac{1}{n_{eff}} + \frac{1}{R}\right\} V_e} = 0.268$$

Where, $F_{\alpha}(1, f_e)$ = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e = 3.99 (from Tabulated F value)

$$n_{eff} = \frac{N}{1 + \text{Total DF involved in estimation of mean}}$$

= 81 / (1+8)

= 9

N = Total number of results = 27 x 3 = 81

R = Sample size for confirmation experiments = 3

V_e = Error variance = 0.0406 (Table 7) f_e = error DOF = 64

Therefore, the predicted confidence interval for confirmation experiments is:

$$\mu_{SR} - CI_{CE} < \mu_{SR} < \mu_{SR} + CI_{CE}$$

$$1.658 < \mu_{SR} < 2.194$$

Exp. No.	MRR			MEAN1	SNRA1	SR			MEAN2	SNRA2
	MRR	MRR 2	MRR 3			Ra 1	Ra 2	Ra 3		
1	32.19	33.168	32.67	32.6760	30.2826	2.192	2.81	2.46	2.48733	-7.9594
2	28.296	29.474	28.89	28.8867	29.2103	2.830	2.126	2.381	2.44567	-7.8290
3	42.262	45.489	43.873	43.8747	32.8325	2.227	2.841	2.638	2.56867	-8.2369
4	20.521	21.337	20.923	20.9270	26.4108	1.889	2.488	2.214	2.19700	-6.8902
5	17.308	18.008	17.652	17.6560	24.9344	1.648	1.857	1.732	1.74567	-4.8497
6	49.851	54.347	52.148	52.1453	34.3275	2.978	2.647	2.727	2.78400	-8.9045
7	12.925	13.548	13.256	13.2430	22.4349	1.605	1.680	1.629	1.63800	-4.2879
8	22.646	23.458	23.054	23.0527	27.2517	2.15	2.447	2.225	2.28467	-7.1890
9	36.942	37.061	37.004	37.0023	31.3646	2.858	3.040	2.971	2.95633	-9.4179
10	52.933	54.026	53.47	53.4763	34.5623	2.852	2.674	2.771	2.76567	-8.8390
11	48.361	48.168	48.269	48.2660	33.6728	2.734	2.801	2.789	2.77467	-8.8647
12	44.761	46.133	45.441	45.4450	33.1477	2.612	3.230	2.981	2.94100	-9.4021
13	36.291	37.646	36.962	36.9663	31.3532	2.617	2.667	2.698	2.66067	-8.5005
14	30.398	31.838	31.121	31.1190	29.8559	2.438	2.542	2.499	2.49300	-7.9357
15	49.255	50.98	50.112	50.1157	33.9969	2.971	2.968	2.987	2.97533	-9.4707
16	24.812	25.097	24.958	24.9557	27.9431	2.484	2.479	2.304	2.42233	-7.6899
17	35.895	37.219	36.551	36.5550	31.2561	2.333	3.086	2.089	2.74267	-8.8189
18	36.648	38.223	36.937	36.9360	31.3384	2.764	3.033	2.915	2.90400	-9.2662
19	55.517	54.68	53.593	54.5967	34.7406	3.066	3.215	3.161	3.14733	-9.9605
20	62.537	64.22	63.37	63.3757	36.0369	3.059	2.995	2.805	2.95300	-9.4111
21	53.846	53.913	53.872	53.8770	34.6281	2.939	3.066	3.001	3.00200	-9.5495
22	38.646	38.475	38.564	38.5617	31.7231	2.889	3.053	2.935	2.95900	-9.4253
23	45.413	44.411	44.916	44.9133	33.0464	3.030	3.053	3.151	3.07800	-9.7666

24	58.102	59.691	58.891	58.8947	35.3999	3.195	3.358	3.236	3.26300	-10.2743
25	26.361	27.068	26.711	26.7133	28.5330	2.550	2.716	2.680	2.64867	-8.4637
26	50.005	53.042	51.528	51.5250	34.2328	3.140	3.242	3.198	3.19333	-10.0856
27	43.889	45.253	44.579	44.5737	32.9795	2.805	2.716	2.865	2.79533	-8.9308

Table 5: Experimental Results of Material Removal Rate and Surface Roughne

Source	DF	Seq SS	Adj MS	F	P
Ton	2	4704.71	2352.36	1243.54	0.000
T_{off}	2	2828.09	1414.04	747.52	0.000
Ip	2	2495.32	1247.66	659.56	0.000
SV	2	2063.22	1031.61	545.35	0.000
T_{on}*T_{off}	4	110.38	27.60	14.59	0.000
T_{on}*Ip	4	1498.81	374.70	198.08	0.000
Error	64	121.07	1.89		
Total	80	13821.60			

S = 1.37538   R-Sq = 99.12%   R-Sq(adj) = 98.91%

Table 6: Analysis of Variance for MRR, using Mean Data

Source	DF	Seq SS	Adj MS	F	P
Ton	2	4704.71	2352.36	1243.54	0.000
T_{off}	2	2828.09	1414.04	747.52	0.000
Ip	2	2495.32	1247.66	659.56	0.000
SV	2	2063.22	1031.61	545.35	0.000
T_{on}*T_{off}	4	110.38	27.60	14.59	0.000
T_{on}*Ip	4	1498.81	374.70	198.08	0.000
Error	64	121.07	1.89		
Total	80	13821.60			

S = 1.37538   R-Sq = 99.12%   R-Sq(adj) = 98.91%

Table 7: Analysis of Variance for Surface Roughness (Mean Data)

Source	DF	Seq SS	Adj MS	F	P
T_{on}	2	5.94699	2.97350	73.22	0.000
T_{off}	2	0.38217	0.19109	4.71	0.012

Ip	2	1.93474	0.96737	23.82	0.000
SV	2	1.67640	0.83820	20.64	0.000
T_{on}*T_{off}	4	0.28574	0.07143	1.76	0.148
T_{on}*Ip	4	1.16430	0.29107	7.17	0.000
Error	64	2.59920	0.04061		
Total	80	13.98955			

S = 0.201526   R-Sq = 81.42%   R-Sq(adj) = 76.78%

Table 8: Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments

Performance Measures/ Responses	Optimal Parameter Combination	Predicted Optimal Value	Predicted Confidence Interval (CI_{CE}) at 95% Confidence Level	Experimental value
Material Removal Rate (MRR)	$A_3B_1C_3D_1$	69.67mm^2/min	67.84≤MRR≤ 71.50	69.317 mm^2/min
Surface Roughness(SR)	$A_1B_3C_1D_3$	1.926µm	1.658 ≤ SR ≤2.194	1.692µm

5. Multi-response optimization using Grey Relation Analysis

An efficient solution of the uncertainty, multiple input and discrete data problem can be find out byGrey Relation Analysis (GRA).Grey relational analysis provides the relation between machining parameters and machining performance. In the present study, a linear normalization of the experimental results (S/N ratios) for Material Removal Rate (MRR) and Surface Roughness (SR) were performed in the range of 0 and 1, which is also called the grey relational generating [1].

In order to optimize the MRR and SR simultaneously using grey relational analysis (GRA), the following steps were followed [1]:

1. By using Taguchi Method Convert the experimental data into S/N values,
2. Normalize the S/N ratio,
3. Grey relational generating is perform and then calculate the grey relational coefficient,
4. By using the concept of weighing factor Calculate the grey relational grade for the performance characteristics,
5. Analyse the experimental results using the grey relational grade and statistical analysis of variance (ANOVA),
6. Select the optimal levels of process parameters,
7. Perform the confirmation experiment to verify the optimal process parameter settings.

In grey relational analysis experimental results were normalized first and then the grey relational coefficient has been calculated from the normalized experimental data. Data pre- processing was performed on raw data (Mean data) for all experimental results (Table 9). Data pre-processing is a technique that involves transforming raw data into an understandable format. Raw data (Mean data) can be normalized by using the following expressions: For MRR Higher the better (Eq. (2))

$$x_i^*(k)=\frac{x_i^0(k)-\min x_i^0(k)}{\max x_i^0(k)-\min x_i^0(k)} \text{ .... for MRR} \quad (2)$$

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

Where $x_i^*(k)$ is the sequence after the data processing; $x_i^0(k)$is the original sequence of S/N ratio, i=1, 2, 3…., m and k =1, 2,…., n *with* m=27 and n=2; max $x_i^0(k)$ is the largest value of $x_i^0(k)$; min$x_i^0(k)$is the smallest value of $x_i^0(k)$. Table 9shows the normalized S/N ratio for the MRR and SR. The outcomes are denoted as $x_0^*(k)$ and $x_i^*(k)$ for reference sequence and comparability sequence, respectively. Basically, the larger normalized S/N ratio corresponds to the better performance and the best-normalized S/N ratio is equal to unity [1].

6. Grey Relational Grade Generation

The grey relational coefficient is calculated to express the relationship between the best (reference) and the actual normalized S/N ratio. The grey relational coefficient is expressed as follows:

$$£_{ij}(k)=\frac{(\Delta)\min-\zeta(\Delta)\max}{(\Delta)oi(k)-\zeta(\Delta)\max} \quad (4)$$

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

Δ_{min} = min [min $\Delta_{oi}(k)$]

Δ_{max} = max [max $\Delta_{oi}(k)$]

$£_{ij}$The grey relational coefficient, ζ is is the distinguishing coefficient which is defined in the range $0 \le \zeta \le 1$.ζ is set as 0.5 in this study.

And hence to calculate the grey relational coefficient from the above equationthe deviation sequence must be calculated. The deviation sequence $(\Delta)oi$ can be calculated as follow:

$(\Delta MRR)o1$ = |*1-0.5769* | = *0.4231*

$(\Delta SR)o1$= |*1-0.6133* | = *0.3867*

The same calculating method was performed for i=1-27, and the results of all $(\Delta)oi$ for i=1-27 are listed in Table (9).

On investigating the data in table (9) we can find the following:

$\Delta_{max} = \Delta_7$ (MRR) = Δ_{24} (SR) = 1.000,

$\Delta_{min} = \Delta_{20}$ (MRR) = Δ_7 (SR) = 0.000,

Next, the grey relational coefficient is calculated from the equation no. (4) and the values are calculated as follows:

$£_{1(MRR)}$ = [0.000 + (0.5 × 1.000)] / [0.4231 + (0.5×1.000) = 0.5416

$£_{1(SR)}$ = [0.000 + (0.5 × 1.000)] / [0.3867 + (0.5×1.000)] = 0.5638

And grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, that is:

$$Y_j = \frac{1}{m}\sum_{i=1}^{m} £ \quad (5)$$

Where γ_j the grey relational grade for the j[th] experiment and m is the number of performance characteristics. The grey relational grade is a weighting-sum of the grey relational coefficients. The overall evaluation of multiple performance characteristics is based on the grey relational grade. Using the same weighting values of MRR and SR (i.e.w_1=w_2=0.5), grey relational grade is calculated.

Table 9: Experimentation data of material removal rate and surface roughness

Sr. no.	Mean (MRR) (Normalized)	Mean (SR) (Normalized)	ΔMRR	ΔSR	GR coeff. (MRR)	GR coeff. (SR)	GR grade S/N ratio	GR grade
1.	0.5769	0.6133	0.4231	0.3867	0.5416	0.5638	-5.15021	0.5527
2.	0.4981	0.5915	0.5019	0.4085	0.4991	0.5503	-5.60178	0.5247
3.	0.7644	0.6596	0.2356	0.3405	0.6797	0.5948	-3.91448	0.6372
4.	0.2923	0.4347	0.7077	0.5653	0.4140	0.4693	-7.09942	0.4416
5.	0.1837	0.0938	0.8163	0.9062	0.3799	0.3555	-8.69013	0.3677
6.	0.8743	0.7711	0.1257	0.2289	0.7991	0.6859	-2.58607	0.7425
7.	0.0000	1.0000	1.0000	0.0000	0.3333	1.0000	-3.52139	0.6667
8.	0.3541	0.4846	0.6459	0.5154	0.4363	0.4924	-6.66403	0.4643
9.	0.6564	0.8569	0.3436	0.1431	0.5927	0.3043	-6.96475	0.4485
10.	0.8915	0.7602	0.1085	0.2398	0.8217	0.6758	-2.51384	0.7487
11.	0.8261	0.7645	0.1739	0.2355	0.7420	0.6798	-2.96383	0.7109
12.	0.7875	0.8543	0.2125	0.1457	0.7018	0.7743	-2.63887	0.7380
13.	0.6556	0.7036	0.3444	0.2964	0.5921	0.6278	-4.29483	0.6099
14.	0.5456	0.6093	0.4545	0.3904	0.5238	0.5615	-5.31040	0.5426
15.	0.8500	0.8657	0.1500	0.1343	0.7692	0.7882	-2.17260	0.7787
16.	0.4049	0.5682	0.5951	0.4318	0.4566	0.5366	-6.07987	0.4966
17.	0.6485	0.7568	0.3515	0.2432	0.5872	0.6727	-4.01457	0.6299
18.	0.6545	0.8316	0.3455	0.1684	0.5852	0.7480	-3.52269	0.6666
19.	0.9046	0.9475	0.0954	0.0525	0.8398	0.9049	-1.18668	0.8723
20.	1.0000	0.8558	0.0000	0.1442	1.0000	0.7761	-1.03076	0.8881
21.	0.8964	0.8789	0.1036	0.1211	0.8283	0.8050	-1.75981	0.8166
22.	0.6828	0.8581	0.3172	0.1419	0.6119	0.7789	-3.15531	0.6954
23.	0.7801	0.9151	0.2199	0.0849	0.6945	0.8548	-2.21285	0.7751
24.	0.9531	0.0000	0.0469	1.0000	0.9142	0.3333	-4.10049	0.6237
25.	0.4483	0.6975	0.5517	0.3025	0.4754	0.6230	-5.20539	0.5492
26.	0.8673	0.9684	0.1327	0.0316	0.7903	0.9405	-1.25566	0.8654
27.	0.7752	0.7755	0.2248	0.2245	0.6898	0.6901	-3.22428	0.6899

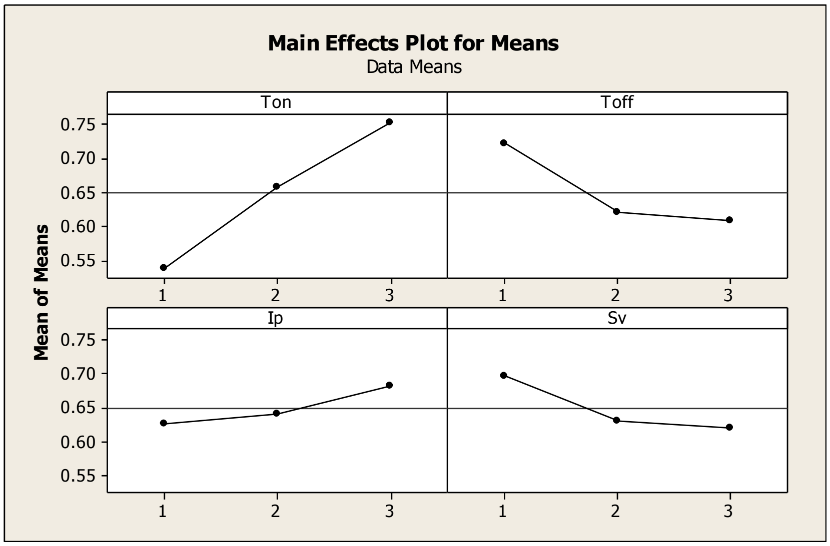

Figure 8: Main Effect plots for Means of G R Grade

7. Results and Discussion

Fig. 4and fig 5 represents the effect of pulse on time on MRR at the chosen machining conditions. It can be observed from the figure that the MRR increased when the pulse on (T_{on}) time was increased due to the number of discharges within a given periodof time increase. Since the amount of material removed from the work specimen highly depends on the discharge energy, it is also seen that with an increase of pulse on time the surface quality of the machined surfaces were decreased because under longer pulse on time the electrical sparks generate bigger craters on the surface of work piece. Fig 4 showsincreasing the peak current results in the increases of number of electrons striking the work surface in a single discharge, which further causes eroding out more material from the work surface per discharge, thereby increase in material removal rate. Fig.4 and fig.5 shows that, the metal removal rate decreases almost constantly with increase in pulse off time (T_{off}) and spark gap set voltage (SV) as less number of sparks are produced at higher value of pulse off time and spark gap set voltage. Fig 6 and fig 7 shows when parameter pulse on time increased the value of Surface Roughness decreases. The pulse off time parameter has direct effect on the Surface roughness, as we increase the pulse off time the value of Surface Roughness also increases.

Table 10: Summary and comparison of results

Method	Optimization technique	Optimal parameters	Experimental values
Single characteristic	Taguchi Method	A3 B1 C3 D1 (MRR)	MRR = 69.317 mm^2/min
Multi-characteristic optimization	Grey relational analysis	A3 B1 C3 D1	MRR = 69.317mm^2/min SR = 2.086 µm

The value of Surface roughness also increases by increasing servo voltage (fig.6). Fig 6 shows that when parameter peak current increases the value of Surface Roughness decreases which is in agreement with the findings of Kumar A., Kumar V., Kumar J. 2012 [2]. Analysis of Variance for MRR and SR is done using Mean data shown in Table 6 and 7 respectively.Figure 8 shows the main effect plots for means of G R Grade. Table 10 shows the comparison of results between single response optimization and multi response optimization using grey relational analysis.

8. Conclusion

1. MRR and SR were optimized individually by the help of Taguchi methodology. Two different optimal settings of process parameters were found for MRR (A3, B1, C3, and D1) and SR (A1, B3, C1 and D3). The material removal rate (MRR) is mostly affected by the pulse-on time, peak current pulse off-time, and servo voltage. The surface roughness values (SR) are influenced mostly by pulse-on time, peak current, pulse off-time, and servo voltage.

2. In case of GRA, grey relational grade was used as a performance index to determine the optimal combination of process parameters for multiple machining characteristics. Both the machining characteristics were given equal importance by assigning equal weights in calculating the grey relational grade. However, with a different set of weights, a different set of optimal parameters for machining characteristics will result. The optimal set predicted will be closer to the optimal set predicted for single characteristic with the largest weight.

3. A single set of parametric combination can never produce the highest productivity (within the possible range) with the best surface finish at high material removal rate. A proper trade-off becomes inevitable to satisfy all the above-mentioned two machining criteria simultaneously.

4. The optimal values obtained using the multi-characteristic optimization model has been validated by confirmation experiments. The optimal setting of process parameters is A3=123 µs, B1 =50µs, C3 =13ampere, D1=30 volt.

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FIGURE LEGEND

TABLE LEGEND