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PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Multi response optimization in wire electrical discharge machining of Inconel X-750 using Taguchi's technique and grey relational analysis

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Abstract: The effective optimization of machining process parameters affects dramatically the cost and production time of machined components as well as the quality of the final products. This study presents an investigation on cutting speed and surface roughness of Inconel X-750 using Wire-cut electric discharge machining process. Six input process parameters of Wire-cut Electro Discharge Machining—spark gap voltage, pulse-on time, pulse-off time, wire feed rate, peak current and wire tension—were chosen to study their effects on the selected responses. Taguchi's design of experiments methodology has been used for planning, designing and conducting the experiments. The grey relational analysis has been applied in conjunction with the Taguchi's parameter design approach for the optimization of multiple responses. The analysis of variance has been applied to identify the significance of different parameters. Finally the confirmation experiments were performed to validate the predicted optimized results.

Subjects: Manufacturing & Processing; Machine Science & Technology; Materials Processing; Engineering Productivity

Keywords: Inconel; WEDM; optimization; ANOVA; grey relational analysis



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PUBLIC INTEREST STATEMENT

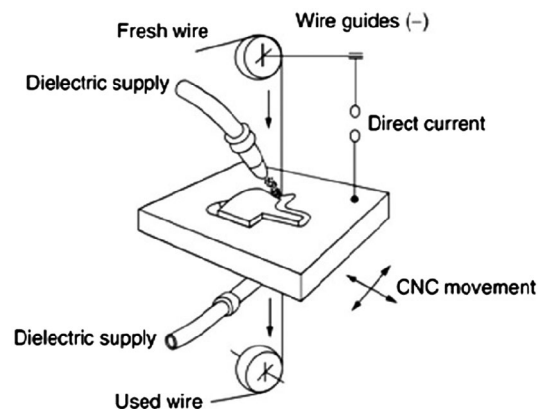
Inconel X-750 is a precipitation-hardenable nickel-chromium alloy used for its corrosion and oxidation resistance and high strength at temperatures up to 1,300°F. It also has excellent properties down to cryogenic temperatures. Inconel alloys are oxidation and corrosion resistant materials well suited for service in extreme environments subjected to pressure and heat. This alloy has a high hardness value ranging in between 302 and 363 BHN. So, it is difficult to machine this material with conventional machining. Wire-cut Electro Discharge Machining (WEDM) can be one option to machine this material as the process is based on the use of thermal energy for machining purpose and can machine any material which is electrically conductive irrespective of its mechanical and physical properties. The outcome of this investigation is likely to shed some light on various issues related to the productivity and surface quality in WEDM of Inconel X-750.

1. Introduction

The demands for alloy materials having high hardness, toughness and impact resistance are increasing at a rapid pace owing to the development of manufacturing industry. Such materials are difficult to machine by conventional machining methods. Further it is sometimes impossible to produce complex geometries with requisite finish and dimensional accuracy in advanced materials by applying the conventional processes. This has led to the development of a number of advanced machining processes and Wire-cut Electro Discharge Machining (WEDM) is one of the most effective non-traditional machining methods to machine difficult to machine materials used in technologically advanced industries like aerospace, nuclear, missile etc. The process uses electro-thermal mechanism of spark erosion similar to the one used in EDM for cutting of the material. The material should be conductive in order to machine with WEDM. The material is cut by a series of isolated electrical discharges between the wire and the work piece. The work piece is submerged in a dielectric fluid which acts as a coolant and plays an important role in machining. When the dielectric fluid is supplied between the wire electrode and work piece, it becomes ionized and the electric discharge takes place. The temperature of the region where discharge occurs is raised to very high level. The work surface gets melted due to this high temperature and thus removed. The dielectric fluid takes away the removed particles. The schematic diagram of WEDM is shown in Figure 1 (El-Hofy, 2003).

It is an established fact that a good surface finish and a high material removal rate (MRR) can never be attained simultaneously in any manufacturing process and WEDM is no exception to it. This is an age-old problem and the researchers from different countries are making continuous efforts to get rid of this problem. The probable solution for this problem is considered as a rough cut which is followed by one or more trim cuts. There is a lot of work done on WEDM in past but a little work has been done on the multi objective optimization of parameters for Inconel X-750. Gökler and Ozanözgü (2000) investigated the effects of cutting parameters on surface roughness (SR) in the WEDM process for different steel materials and optimal condition was obtained. The experimental results can be used in industry in order to select the best suitable parameter combination to get the required surface roughness values for the products. Miller, Shih, and Qu (2003) studied the effect of two input factors i.e. spark on-time duration and spark on-time ratio in WEDM. The MRR and surface integrity were selected as the responses of interest. Four types of advanced material i.e. porous metal foams, metal bond diamond grinding wheels, sintered Nd-Fe-B magnets and carbon-carbon bipolar plates were used. It was concluded that the metal foams is difficult to machine without damaging the ligaments, the diamond grinding wheel is very difficult to machine to the precise shape, sintered Nd-Fe-B magnet material is very brittle and easily chipped by using traditional machining methods, carbon-carbon bipolar plate is delicate but can be machined easily by the WEDM. Tosun and Cogun (2003) studied the effects of cutting parameters on the wear of the tool wire. The pulse duration, open circuit voltage, wire speed and dielectric fluid pressure were taken as the input parameters. AISI 4140 steel of 10 mm thickness was used as work material. It was found that the increasing pulse duration and open circuit voltage increase the WWR whereas the increasing wire speed and dielectric fluid pressure decrease the WWR. Liao, Huang, and Chen (2004) investigated the

Figure 1. Schematic diagram of WEDM.



machining characteristics of Wire-EDM to achieve a fine surface finish. The traditional circuit was modified using low power for ignition and for machining as well. Hasçalık and Çaydaş (2004) undertook a study to machine AISI D5 tool steel on wire electrical discharge machining. Open circuit voltage, pulse duration, wire speed and dielectric fluid pressure were taken as the input factors to observe their effects on surface roughness and metallurgical structure. It was found that the intensity of the process energy does affect the amount of recast and surface roughness as well as micro cracking, while the wire speed and dielectric fluid pressure do not seem to have any significant influence. Kuriakose and Shunmugam (2005) investigated multi-objective optimization of wire EDM process. Titanium alloy (Ti6Al4 V) was taken as the work material. The non-dominated sorting genetic algorithm (NSGA) was employed for the multi-objective optimization. Chiang and Chang (2006) optimized the process parameters of wire electric discharge machining process with Al_2O_3 particle reinforced material (6061 alloy) as the work material. The cutting removal rate and the surface roughness were simultaneously improved using grey relational analysis (GRA). Kanlayasiri and Boonmung (2007) investigated the effects of machining variables on the surface roughness of wire-EDMed DC53 die steel. Results showed that pulse-on time and pulse-peak current are significant variables in affecting surface roughness. The surface roughness of the test specimen increases when these two parameters increase. Ramakrishnan and Karunamoorthy (2008) developed artificial neural network models to predict and select the best cutting parameters of WEDM process for the machining of Inconel 718. It was identified that the pulse on time, delay time and ignition current had more influence than the wire feed speed on MRR and SR. Shichun et al. (2009) studied and analyzed the variation in kerf width in micro-WEDM. The authors developed a mathematical model for lateral vibration in the wire and obtained an analytical solution for it. Singh and Garg (2009) investigated the effects of various process parameters of WEDM on MRR of hot die steel H-11 using one factor at a time approach. They found that the MRR directly increases with increase in pulse on time and peak current while decreases with increase in servo voltage and pulse off time. Antar, Soo, Aspinwall, Jones, and Perez (2011) machined Udimet 720 nickel based super alloy and Ti-6Al-2Sn-4Zr-6Mo titanium alloy using Cu core coated wires (ZnCu50 and Zn rich brass) as tool on Wire EDM. The authors concluded that the productivity increased by about 40% for Udimet 720 and about 70% for Ti6246 when standard uncoated brass wire was replaced by diffusion annealed coated wires keeping the input parameters at the same setting. Muthuraman and Ramakrishnan (2012) studied the MRR and surface roughness of the WC-Co composite material subjected to wire electric discharge machining using desirability analysis. The surface roughness improved from 2.52 to 1.90 μm and MRR increased from 19.52 to 21.24 mm^3/min . Shandilya, Jain, and Jain (2012) applied response surface methodology to optimize the process parameters of WEDM. $SiC_p/6061Al$ metal matrix composite was chosen as the work material. Results showed that voltage and wire feed rate are highly significant parameters and pulse-off time is less significant. Pulse-on time has insignificant effect on kerf. Jangra, Grover, and Aggarwal (2012) optimized the multi machining characteristics in wire electrical discharge machining of WC-5.3%Co composite. Taguchi's design of experiment was used. The four characteristics optimized simultaneously were MRR, surface roughness, angular error and radial overcut. The GRA coupled with entropy measurement was employed. Rajyalakshmi and Venkata Ramaiah (2013) applied Taguchi GRA in order to obtain improved MRR, surface roughness and spark gap. The MRR got increased from 119.625 to 126.85 mm^3/min , the surface roughness was reduced from 1.68 to 1.44 μm and the spark gap was reduced from 0.015 to 0.013 mm. Khan, Khan, Siddiquee, and Chanda (2014) investigated the effect of the WEDM parameters on the surface roughness and the micro hardness of the high strength low alloy steel (ASTM A572-grade 50). Nine experimental runs based on an orthogonal array of Taguchi method were performed and GRA method was subsequently applied to determine an optimal WEDM parameter setting. The pulse off-time was found to be the most influential factor. Chalisgaonkar and Kumar (2014) optimized the MRR, surface roughness and wire weight consumption simultaneously using grey-fuzzy logic and dimensional analysis. Surface integrity aspects of the selected machined titanium samples were also investigated to assess the suitability of WEDM for machining titanium. Goswami and Kumar (2014a) presented a study

on multi response optimization using utility concept for wire electric discharge machining of Nimonic-80A alloy. The MRR and surface roughness were chosen as the responses to be investigated. Venkataramaiah and Rajyalakshmi (2015) optimized the multi response characteristics such as such as MRR, surface finish and spark gap of WEDM on Inconel-825 super alloy using fuzzy-GRA. It was concluded that Taguchi, fuzzy-GRA can efficaciously be used to find the optimal combination of influential input parameters of WEDM. Jangra (2015) presented the investigation on multi-pass cutting operation (single rough cut followed by multi trim cuts) in wire electrical discharge machining of WC-5.3%Co composite. Trim cuts were performed using Taguchi's design of experiment method to investigate the influence of rough cut history, discharge current, pulse-on time, wire offset and number of trim cuts on two performance characteristics namely depth of material removed and surface roughness. Result showed that the surface finish improved significantly in trim cutting operation irrespective of the rough cutting operation, while depth of material removed was proportional to the number of trim cuts followed.

The reported literature reflects a complete dearth of research on multi-response optimization while machining Inconel X-750 on WEDM. Inconel X-750 is a precipitation-hardenable nickel-chromium alloy used for its corrosion and oxidation resistance and high strength at temperatures up to 1,300°F. The current article is thus targeted to analyse the effect of input factors of WEDM on surface roughness and cutting speed while machining Inconel X-750. GRA in conjunction with Taguchi's technique has been applied for the multi response optimization.

2. Materials and methods

Experiments were performed on Electronica sprintcut CNC wire cut EDM machine tool to study cutting speed (CS) and surface roughness (SR) at different settings of pulse on time (T_{ON}), pulse off time (T_{OFF}), spark gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT). The levels of the input parameters were selected on the basis of literature survey and a pilot study using one factor at a time approach. Each factor was varied over a wide range keeping all others at their mean value and the trend of influence of each factor was obtained in the pilot study. Taguchi's L_{27} orthogonal array with assignments of six input variables and 3 interactions (Table 1) was selected for final experimentation.

The various input parameters with their levels are incorporated in Table 2.

The material used in this study is Inconel X-750 which is a nickel based alloy. The chemical composition of the work material in wt % is as: Ni 70, Cr 14–17, Fe 5–9, Nb 0.7–1.2, Co 1, Mn 1, Cu 0.5, Al 0.4–1, Ti 2.25–2.75, Si 0.5, C 0.08 and S 0.01. A plate with dimensions 150*100*23 mm has been taken for the experimental work. The main applications of this material are in gas turbines and turbine blades, bolts, forming tools, extrusion dies, heat treating and nuclear reactor applications. Due to its vast applications in various fields, Inconel X-750 is chosen as the work material. The specimens are cut out in cylindrical shape of base diameter 5 mm from the workpiece plate.

The deionized water was used as the dielectric fluid. Digital stop watch was utilized to keep count of the time taken for the experiments. Three trials were conducted for each experiment planned and their mean was taken as the final reading for that particular setting. The time taken for each experiment was recorded and the cutting speed was calculated by dividing the circumference of cutting cylindrical piece by time taken to cut it completely. Surface roughness (R_a) was measured using SURFCOM FLEX roughness tester. Table 3 gives the readings for CS and SR for different settings of parameters.

Table 1. L₂₇ orthogonal array with six input parameters and three interactions assigned

Run	1	2	3	4	5	6	7	8	9	10	11	12	13
	A	B	A*B	A*B	C	A*C	A*C	B*C	D	E	B*C	F	-
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 2. Input parameters and their levels

Symbols	Factors	Levels			Unit
		I	II	III	
A	T _{ON}	110	116	122	Machine unit
B	T _{OFF}	37	44	51	Machine unit
C	SV	25	45	65	Volt
D	IP	90	130	170	Ampere
E	WF	5	8	11	m/min
F	WT	5	8	11	Machine unit

Table 3. Experimental data of cutting speed and surface roughness

S. No.	CS1	CS2	CS3	S/N ratio	Mean	SR1	SR2	SR3	S/N ratio	Mean
1	0.581	0.586	0.587	-4.6621	0.584667	1.725	2.119	1.629	-5.2803	1.8243
2	1.033	1.035	1.036	0.29599	1.034667	2.416	2.563	2.478	-7.9114	2.4856
3	0.629	0.632	0.634	-3.99038	0.631667	1.638	2.45	1.619	-5.7621	1.9023
4	1.051	1.069	1.052	0.483449	1.057333	2.63	2.792	2.33	-8.2696	2.5840
5	0.759	0.767	0.766	-2.33842	0.764000	2.509	2.146	2.113	-7.0941	2.2560
6	0.474	0.454	0.462	-6.68621	0.463333	1.824	1.682	1.672	-4.7478	1.7260
7	0.647	0.658	0.659	-3.6805	0.654667	1.914	1.74	2.124	-5.7218	1.9260
8	0.396	0.399	0.398	-8.00974	0.397667	1.583	1.614	1.688	-4.2380	1.6283
9	0.329	0.338	0.332	-9.55275	0.333000	1.486	1.517	1.576	-3.6755	1.5263
10	2.115	2.137	2.124	6.548306	2.125333	3.401	3.581	3.472	-10.845	3.4846
11	1.867	1.794	1.826	5.240808	1.829000	3.272	3.284	3.295	-10.327	3.2836
12	1.031	1.033	1.035	0.281974	1.033000	1.852	1.936	1.984	-5.6875	1.9240
13	1.372	1.376	1.378	2.768116	1.375333	3.033	3.684	3.564	-10.727	3.4270
14	1.071	1.08	1.075	0.63071	1.075333	3.107	2.909	2.972	-9.5341	2.9960
15	0.969	0.989	0.976	-0.19415	0.978000	3.014	2.814	2.732	-9.1145	2.8533
16	0.893	0.895	0.897	-0.96358	0.895000	2.782	2.971	2.705	-9.0097	2.8193
17	0.872	0.827	0.854	-1.40761	0.851000	2.712	2.922	2.673	-8.8532	2.7690
18	0.65	0.654	0.658	-3.68877	0.654000	2.314	2.264	2.275	-7.1755	2.2843
19	2.342	2.347	2.349	7.406540	2.346000	4.158	4.127	4.118	-12.328	4.1343
20	1.759	1.778	1.767	4.949393	1.768000	3.046	3.182	3.148	-9.8994	3.1253
21	1.924	1.939	1.946	5.739309	1.936333	3.412	3.582	3.374	-10.774	3.4560
22	1.719	1.732	1.726	4.739015	1.725667	2.924	3.382	2.864	-9.729	3.0566
23	2.033	2.049	2.052	6.212233	2.044667	3.398	3.943	3.848	-11.451	3.7296
24	1.512	1.526	1.528	3.648007	1.522000	2.742	2.846	3.272	-9.4323	2.9533
25	1.599	1.635	1.624	4.185592	1.619333	3.932	3.445	3.598	-11.279	3.6583
26	1.327	1.339	1.346	2.524344	1.337333	2.548	2.614	2.785	-8.4678	2.6490
27	0.559	0.56	0.565	-5.01587	0.561333	1.742	1.725	1.891	-5.0451	1.7860

3. Single response optimization

The Taguchi's technique is used for single response optimization. The selected characteristic, cutting speed (CS), is of the type "Higher the Better". The S/N ratio is calculated by the logarithmic transformation of loss function (Ross, 1996) as in equation 1 and values are reported in Table 3 along with the raw data.

$$S/N \text{ ratio}_{CS} = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \tag{1}$$

Surface roughness is of the type "Lower the Better". The S/N ratio is calculated as

$$S/N \text{ ratio}_{SR} = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \tag{2}$$

ANOVA test has been conducted using MINITAB-17 software in order to investigate the significance of input parameters. The analysis of variance (ANOVA) results for S/N data for CS and SR are given in Tables 4 and 5 respectively. The insignificant parameters have been discarded from the further analysis.

Table 4. Analysis of variance (S/N ratio) for CS

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p
T _{ON}	2	301.363	301.363	150.681	208.82	0.005
T _{OFF}	2	134.148	134.148	67.074	92.96	0.011
SV	2	79.705	79.705	39.852	55.23	0.018
IP	2	46.778	46.778	23.389	32.41	0.030
WF	2	1.557	1.557	0.779	1.08	0.481
WT	2	4.132	4.132	2.066	2.86	0.259
T _{ON} *T _{OFF}	4	6.783	6.783	1.696	2.35	0.320
T _{ON} *SV	4	0.435	0.435	0.109	0.15	0.946
T _{OFF} *SV	4	10.403	10.403	2.601	3.60	0.229
Residual error	2	1.443	1.443	0.722		
Total	26	586.747				

Notes: S = 0.8495; R² = 99.8%; R²(adj.) = 96.8%

Table 5. Analysis of variance (S/N ratio) for SR

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p
T _{ON}	2	79.343	79.343	39.671	84.13	0.012
T _{OFF}	2	19.037	19.037	9.518	20.18	0.047
SV	2	28.564	28.564	14.281	30.29	0.032
IP	2	21.470	21.470	10.735	22.76	0.042
WF	2	0.867	0.867	0.433	0.92	0.521
WT	2	0.828	0.828	0.414	0.88	0.533
T _{ON} *T _{OFF}	4	3.966	3.966	0.991	2.10	0.347
T _{ON} *SV	4	1.767	1.767	0.441	0.94	0.575
T _{OFF} *SV	4	2.646	2.646	0.661	1.40	0.457
Residual error	2	0.943	0.943	0.471		
Total	26	159.431	159.431			

Notes: S = 0.6867; R² = 99.4%; R²(adj.) = 92.3%

For cutting speed,

The overall mean is: $\mu = 1.1702$ mm per min

The predicted optimum value for CS is calculated as

$$\mu_{CS} = (\mu_{A3} + \mu_{B1} + \mu_{C1} + \mu_{D2}) - 3\mu = 2.3238 \text{ mm per min} \quad (3)$$

For calculation of confidence interval, Equation (4) has been used (Ross, 1996).

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e) \cdot V_e \left\{ \frac{1}{n_{eff}} + \frac{1}{R} \right\}} \quad (4)$$

Here f_e (error degree of freedom) = 2; $F_{0.05}(1, 2) = 18.51$ (Tabulated value at 95% confidence level); V_e (error variance) = 0.00844

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

N = total number of experiments = 81

Hence, $n_{\text{eff}} = 81/(1 + 8) = 9$; R = sample size = 3.

Putting all values in Equation (4)

$$CI_{\text{CE}} = 0.2635$$

The 95% confidence interval for μ_{CS} is $2.0603 < \mu_{\text{CS}} < 2.5873$

Similarly for surface roughness (SR),

The overall mean is: $\mu = 2.6758 \mu\text{m}$

The predicted optimum value for SR is calculated as

$$\mu_{\text{SR}} = (\mu_{\text{A3}} + \mu_{\text{B1}} + \mu_{\text{C1}} + \mu_{\text{D2}}) - 3\mu = 0.8838 \mu\text{m} \quad (5)$$

For calculation of confidence interval, Equation (6) has been used (Ross, 1996).

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

Here f_e (error degree of freedom) = 2; $F_{0.05}(1, 2) = 18.51$ (Tabulated value at 95% confidence level); V_e (error variance) = 0.02478

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

$N = 81$, Hence, $n_{\text{eff}} = 81/(1 + 8) = 9$; $R = 3$

Putting the values in Equation (6)

$$CI_{\text{CE}} = 0.4515$$

The 95% confidence interval for μ_{SR} is $0.4323 < \mu_{\text{SR}} < 1.3353$

The confirmatory experiments were performed three times at the optimal settings of parameters. The mean value of the responses has been found to be within confidence intervals.

4. Multi response optimization using grey relational analysis

The GRA has been used for multi response optimization. It gives an effective solution to the ambiguity, multi input and isolated data problem. The relationship between input parameters and outputs can be established using GRA (Goswami & Kumar, 2014b). The various steps followed in the GRA are shown in Figure 2.

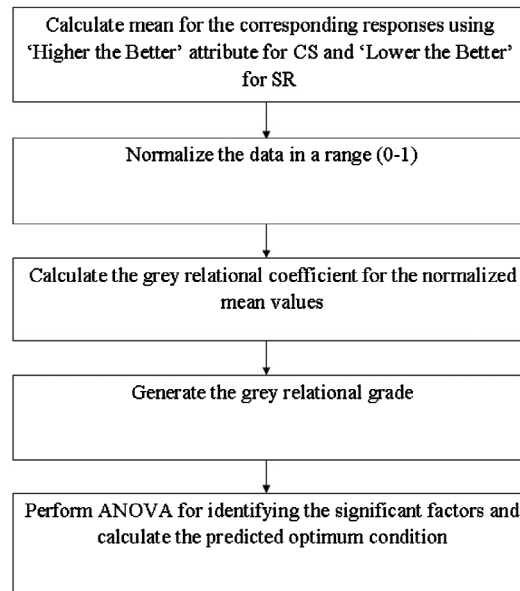
Raw data can be normalized using the following expressions:

For CS Higher the Better (Equation (7))

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (7)$$

For SR Lower the Better (Equation (8))

Figure 2. Steps involved in GRA.



$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad (8)$$

where $x_i^*(k)$ is the string after the calculation; $x_i^o(k)$ is the original string of raw data, $i = 1, 2, 3 \dots m$ and $k = 1, 2 \dots n$ with $m = 27$ and $n = 2$; $\max x_i^o(k)$ is the maximum value of $x_i^o(k)$; $\min x_i^o(k)$ is the minimum value of $x_i^o(k)$.

The grey relational coefficient (GRC) is calculated to express the relation between the best and mean data as follows:

$$\xi_{ij}(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}} \quad (9)$$

where, $\Delta_{oi}(k)$ is the divergence of reference sequence which can be calculated as

$$\Delta_{oi}(k) = |1 - x_i^*(k)|, \Delta_{min} = \min (\Delta_{oi}(k)), \Delta_{max} = \max (\Delta_{oi}(k))$$

and ζ is the distinguishing coefficient and usually it is set as 0.5

The grey relational grade (GRG) is computed by assigning equal weights (0.5) for both the responses by the following equation:

$$GRG = \sum_{i=1}^n w \xi \quad (10)$$

where n is number of performance characteristics; w is weight assigned to the characteristic; ξ is the corresponding GRC for the characteristics

The values of GRC and GRG are shown in Table 6.

The GRG is now taken as the single response and is optimized using the Taguchi technique in MINITAB-17.

Table 6. Grey relational grade data

S. No.	Mean CS normalized	Mean SR normalized	Δ_{CS}	Δ_{SR}	GR coefficient (CS)	GR coefficient (SR)	GRG
1	0.622	0.886	0.378	0.114	0.5695	0.8143	0.6919
2	0.348	0.632	0.652	0.368	0.4340	0.5760	0.5050
3	0.148	0.856	0.852	0.144	0.3698	0.7764	0.5731
4	0.359	0.594	0.641	0.406	0.4382	0.5518	0.4950
5	0.214	0.720	0.786	0.280	0.3888	0.6410	0.5149
6	0.064	0.923	0.936	0.077	0.3481	0.8665	0.6073
7	0.159	0.846	0.841	0.154	0.3728	0.7645	0.5686
8	0.032	0.961	0.968	0.039	0.3406	0.9276	0.6341
9	0	1	1	0	0.3334	1	0.6667
10	0.890	0.249	0.110	0.751	0.8196	0.3997	0.6096
11	0.743	0.326	0.257	0.674	0.6605	0.4259	0.5432
12	0.348	0.847	0.652	0.153	0.4340	0.7657	0.5998
13	0.517	0.271	0.483	0.729	0.5086	0.4068	0.4577
14	0.368	0.436	0.632	0.564	0.4417	0.4699	0.4558
15	0.321	0.491	0.679	0.509	0.4241	0.4955	0.4598
16	0.279	0.504	0.721	0.496	0.4095	0.5020	0.4557
17	0.257	0.523	0.743	0.477	0.4023	0.5117	0.4570
18	0.159	0.709	0.841	0.291	0.3728	0.6321	0.5024
19	1	0	0	1	1	0.3334	0.6667
20	0.713	0.387	0.287	0.613	0.6353	0.4492	0.5422
21	0.796	0.259	0.204	0.741	0.7102	0.4029	0.5565
22	0.692	0.413	0.308	0.587	0.6188	0.4599	0.5393
23	0.851	0.155	0.149	0.845	0.7704	0.3717	0.5710
24	0.591	0.453	0.409	0.547	0.5501	0.4775	0.5138
25	0.639	0.183	0.361	0.817	0.5807	0.3796	0.4801
26	0.499	0.569	0.501	0.431	0.4995	0.5371	0.5183
27	0.113	0.900	0.887	0.100	0.3605	0.8333	0.5969

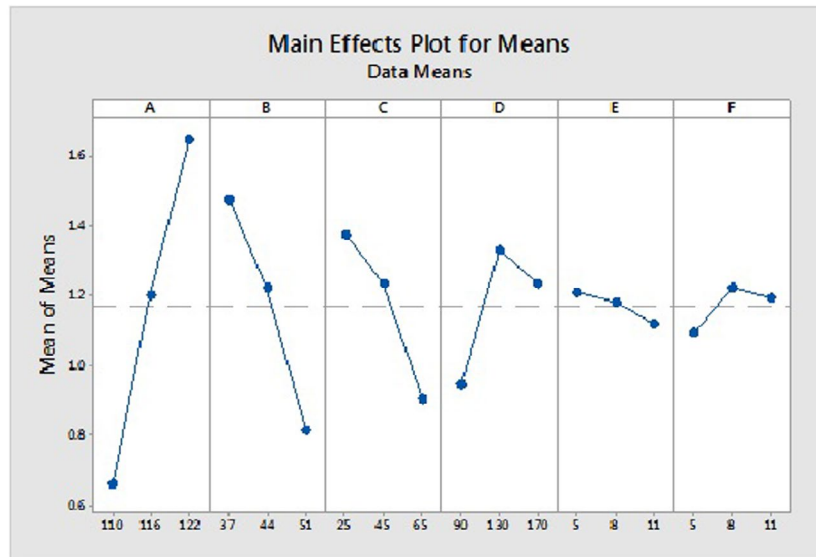
5. Results and discussion

The cutting speed increases with the increase in pulse on time and peak current and vice versa. This is because when we increase the pulse on time and peak current, the number of electrons striking the work surface increases which results in erosion of more material from the work surface. Similarly, CS decreases with the decreased value of SV and T_{OFF} . It is clearly seen from Figure 3. In the single response optimization, the CS and SR are optimized using Taguchi approach. For 95% confidence interval, an input factor should have a P value less than 0.05 in order to have significant effect on the output. From the ANOVA Table 4, it is evident that the T_{ON} , T_{OFF} , SV and IP have p value less than 0.05 and hence show a significant effect on cutting speed. The wire feed, wire tension, and all the three interactions (i.e. $T_{ON} * T_{OFF}$, $T_{ON} * SV$ and $T_{OFF} * SV$) have p value more than 0.05 and hence are insignificant. Figure 3 shows the main effects plot of cutting speed versus T_{ON} , T_{OFF} , SV, IP, WF and WT.

According to this figure, the optimized levels of the parameters for maximum cutting speed are— level 3 of T_{ON} , level 1 of T_{OFF} , level 1 of SV, level 2 of IP, level 1 of WF and level 2 of WT.

Table 5 shows the ANOVA results for surface roughness. According to Table 5, T_{ON} , T_{OFF} , SV and IP are found to be significant factors affecting surface roughness. The three interactions and the two

Figure 3. Main effects plot of cutting speed.



factors (WF and WT) are found to be insignificant. Figure 4 depicts the main effects plot of surface roughness versus T_{ON} , T_{OFF} , SV, IP, WF and WT. From Figure 4, the optimized condition for minimum surface roughness is—level 3 of SV, level 1 of T_{ON} , level 3 of T_{OFF} , level 3 of WF, level 1 of IP and level 1 of WT.

Table 7 shows the comparison between single response optimization using Taguchi’s approach and multi response optimization using GRA. Figure 5 shows the main effects plot for GRG.

Since higher GRG reflects the proximity to the quality characteristics, so it is of ‘higher the better’ type characteristic. As illustrated in the Figure 5, the optimum condition of input factor corresponding to maximum GRG is A1B1C3D1E1F3 i.e. pulse on time-110, pulse off time-37, spark gap voltage-65 V, peak current-90 A, wire feed-5, wire tension-11. The confirmation experiments were also performed at the optimum condition and the values are tabulated.

Figure 4. Main effects plot of surface roughness.

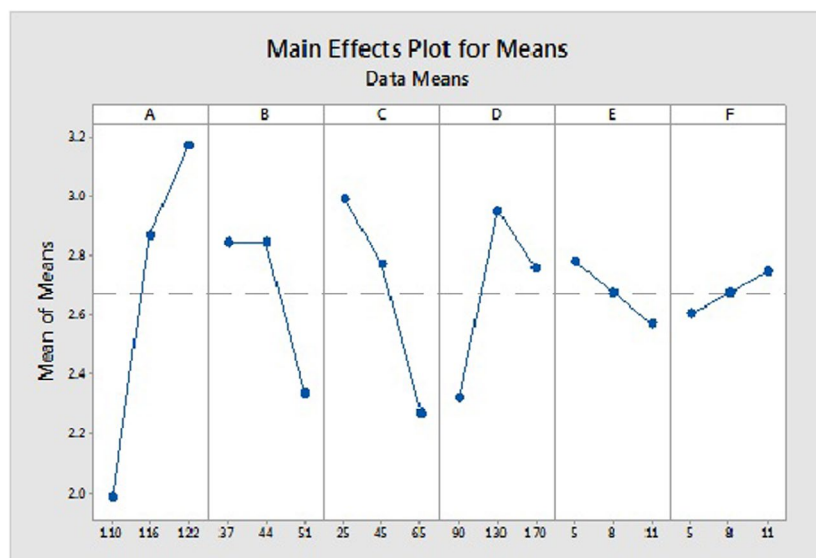
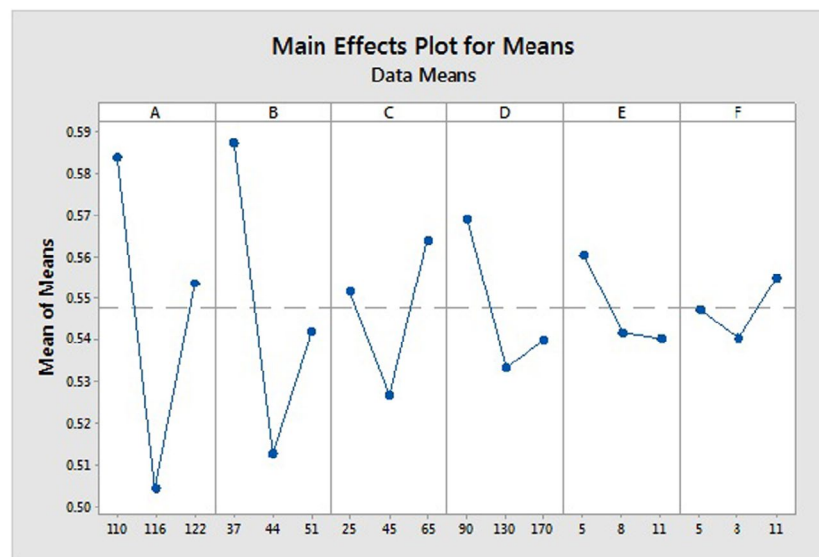


Table 7. Comparison of single response optimization and multi response optimization

Method	Response	Optimal condition	Optimum predicted value	Confirmatory value
Single response optimization	Cutting speed	A3B1C1D2E1F2	2.3238 mm/min	2.3699 mm/min
	Surface roughness	A1B3C3D1E3F1	0.8839 μm	1.246 μm
Grey relational analysis	Cutting speed	A1B1C3D1E1F3	-	1.5246 mm/min
	Surface roughness		-	2.119 μm

Figure 5. Main effects plot of GRG.



6. Conclusions

In this work an attempt was made to determine the important machining parameters for performance measures like cutting speed, surface roughness in the WEDM process. Taguchi's experimental design method is used to obtain optimum parameter combination for maximization of MRR and minimization of surface roughness. Following conclusions can be drawn from this investigation:

- (1) The four factors i.e. pulse on time (T_{ON}), pulse off time (T_{OFF}), spark gap voltage (SV) and peak current (IP) are found to be significant in affecting both the selected responses—cutting speed and surface roughness. The remaining two factors (WF and WT) and the three interactions ($T_{ON} * T_{OFF}$, $T_{ON} * SV$ and $T_{OFF} * SV$) have no significant effect on the characteristics.
- (2) The optimized values of cutting speed and surface roughness attained through single response optimization have been found to be 2.3699 mm per min and 1.246 μm respectively.
- (3) The optimum value of surface roughness was obtained at pulse on time-110; pulse off time-51; spark gap voltage-65 V; peak current-90 A; wire feed-11; wire tension-5.
- (4) The best cutting speed was obtained at pulse on time-122; pulse off time-37; spark gap voltage-25 V; peak current-130 A; wire feed-5; wire tension-8.
- (5) For multi response optimization, the optimal parametric setting has been obtained as pulse on time-110; pulse off time-37; spark gap voltage-65 V; peak current-90 A; wire feed-5; wire tension-11. The confirmation experimental values of CS and SR at the optimal condition are 1.5246 mm per min and 2.119 μm respectively.

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