Chapter 32
Optimization of Process Parameters in WEDM on Inconel 600 Using Central Composite Design and Grey Relational Analysis

Chinta Naga Satya Kirti and M. V. Jagannadha Raju

Abstract Wire electric discharge machining [WEDM] is a method of cutting materials which are electrically conductive in nature by following a well-defined programmed path according to the requirement. Inconel 600 is a nickel–chromium alloy generally used where corrosion and high temperature resistance are in utmost demand. The present work demonstrates the optimization of WEDM process parameters of Inconel 600 with multiple performance characteristics such as material removal rate (MRR), surface roughness (SR) and kerf width (K). The process parameters considered in this research work are peak current, servo voltage, pulse on time and pulse off time. Face-centred central composite design (FCCCD) is used to conduct the experiments on WEDM. Grey relational analysis (GRA) has been used to optimize the process parameters.

Keywords Metal removal rate · Surface roughness · Kerf width · Face-centred central composite design · Grey relational analysis

32.1 Introduction

Wire electric discharge machining (WEDM) is being widely used in manufacturing industries to machine intricate profiles. WEDM has been evolved from a simple method of making tools and dies to the best alternatives of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality [1].

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It is a thermoelectric process in which heat energy in the form of spark is used to remove material from the workpiece. The dielectric fluid (deionized water) having low viscosity and high cooling rate is fed continuously to the machining area to flush away the eroded particles [2]. Conventional machining of nickel–chromium alloys has problems such as poor surface quality, low-dimensional accuracy, high tool wear rate and poor machinability [3]. Non-traditional machining techniques such as water jet machining (WJM) and laser beam machining (LBM) can be used, but the machining equipment is expensive, height of the workpiece is a constraint, and surface finish obtained is not good [4, 5].

Wire electric discharge machining [WEDM] as shown in Fig. 32.1 was used for machining of different materials with good precision, but it is affected by a large number of input parameters which make it difficult to obtain better results such as surface roughness, material removal rate and kerf width [6]. So that optimal selection of process parameters is required to achieve higher metal removal rate and better surface finish simultaneously [7]. The selection of optimum machining parameters in WEDM is an important step [8, 9]. Gowri et al. [10] investigated the effects of WEDM process parameters, particularly cutting speed, feed and depth of cut on Inconel. Dabade et al. [11] studied the effect of process parameters like MRR, SR, kerf width and dimensional deviation on Inconel 718.

Inconel 600 is used in broad applications where it is excellent resistance to corrosion and could withstand high temperatures and used in nuclear reactors where no indication of chloride-ion stress-corrosion cracking in reactor water system has been detected. The basic objective to obtain is the material which is used for a

Fig. 32.1 Wire electric discharge machine [WEDM]

number of applications should have good multiple performance characteristics within the given input process parameters.

32.2 Experimentation

Experiments were performed on Electronica Sprintcut (Electra-Elplus 40A DLX) CNC WEDM. Face-centred central composite design (FCCCD) with four process parameters and five levels was selected for experimentation [12]. The machining parameters are pulse on time (T_{on}), pulse off time (T_{off}), spark gap set voltage (SV) and peak current (IP). Table 32.1 shows chemical composition of Inconel 600, and Table 32.2 shows various process parameters with the corresponding levels.

The fixed process parameters which are considered for machining are wire tension 8 g, wire feed 4 mm/min, servo feed 2200 and pulse peak voltage 1. Thirty experiments were conducted on wire EDM.

Table 32.3 shows the input process parameters and output responses after machining. Machining is done using zinc-coated brass wire electrode of 0.25 mm diameter.

The surface roughness value in μm was obtained by using Mitutoyo SJ-201. The SR values of the WEDM surface were obtained by taking the average roughness values of 5 mm length measurement [13]. The kerf width was taken as average of top width and bottom width and measured by using video measuring system. The material removal rate (MRR) was calculated by Eq. (32.1).

$$MRR = \{K \times t \times d\}/T \quad mm^3/min \tag{32.1}$$

where K is the kerf width in (mm), t is the thickness of workpiece (mm), d is the length of depth of cut (mm), and T is the machining time in (min) [14]. Kerf width was measured on video measurement system as shown in Fig. 32.2.

Table 32.1 Chemical composition of Inconel 600

Element	Nickel + Cobalt	Chromium	Iron	Carbon	Manganese	Sulphur	Silicon	Copper
Content %	72 min	14–17	6–10	0.15 max	1.0 max	0.015 max	0.5 max	0.5 max

Table 32.2 Input process parameters for machining

Parameters	Units	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5
Peak current (IP)	A	A	110	120	130	140	150
Servo voltage (SV)	V	B	50	55	60	65	70
Pulse on time (T_{on})	μs	C	100	105	110	115	120
Pulse off time (T_{off})	μs	D	40	44	48	52	56

Table 32.3 Face-centred central composite design with factors and responses

Expt. No	Peak current (A)	Voltage (V)	Time on (µs)	Time off (µs)	Kerf width (K) (mm)	Metal removal rate (MRR) (mm³/min)	Surface roughness (SR) (µm)
	A	B	C	D			
1	120	55	115	44	0.302	6.177	2.540
2	120	65	105	52	0.293	1.003	1.810
3	130	60	100	48	0.293	0.180	0.970
4	140	65	115	52	0.311	3.659	2.585
5	130	60	110	56	0.302	1.776	2.238
6	140	55	105	52	0.311	1.386	1.798
7	120	65	115	52	0.311	3.312	2.225
8	140	65	105	44	0.283	1.763	1.928
9	130	70	110	48	0.302	2.303	2.030
10	130	60	110	48	0.311	2.978	2.113
11	140	65	115	44	0.293	5.671	2.568
12	140	65	105	52	0.292	1.079	1.823
13	110	60	110	48	0.311	3.110	1.980
14	150	60	110	48	0.320	3.349	2.175
15	130	60	110	48	0.311	2.916	2.163
16	130	60	110	40	0.302	3.698	2.160
17	120	65	115	44	0.302	5.227	2.358
18	140	55	115	52	0.311	4.306	2.255
19	140	55	105	44	0.302	2.228	1.773
20	130	60	110	48	0.292	2.752	1.998
21	130	50	110	48	0.302	3.398	2.268
22	130	60	110	48	0.302	2.817	1.913
23	140	55	115	44	0.311	6.911	2.363
24	120	55	105	44	0.302	1.977	1.768
25	130	60	120	48	0.311	2.592	2.430
26	120	55	105	52	0.302	1.197	1.603
27	120	65	105	44	0.302	1.628	1.635
28	120	55	115	52	0.302	3.723	2.388
29	130	60	110	48	0.311	2.931	2.145
30	130	60	110	48	0.302	2.831	2.148

32.3 Multi-objective Optimization

Deng [15] proposed grey relational analysis [GRA] to deal with uncertain and incomplete systems. GRA is getting tremendous popularity in the recent years because of its ability to determine multiple performance measures. The optimization of multiple performance characteristics using GRA includes the following steps:

Fig. 32.2 Kerf width

- Identification of performance characteristics and process parameters to be evaluated.
- Selection of process parameters levels.
- Selection of central composite design and assigning the process parameters.
- Experimentation as per the design.
- Normalization of the experimental results.
- Determination of deviation sequences.
- Determination of grey relational coefficient (GRC).
- Determination of grey relational grade (GRG).
- Determination of optimal parameters.
- Prediction of GRG under optimal parameters.

32.3.1 Normalization Sequence

In grey relational analysis, data pre-processing is first performed in order to normalize the raw data for analysis. Normalization is a transformation performed on a single data input to distribute the data evenly and scale it into an acceptable range for further analysis. In this study, a linear normalization is performed in the range between zero and unity, which is also called grey relational normalization [8]. Y_{ij} is normalized as Z_{ij} ($0 \leq Z_{ij} \leq 1$) by the following formula to avoid the effect of adopting different units and to reduce the variability. The normalized material removal rate corresponding to the larger-the-better criterion can be expressed as given by Eq. (32.2).

$$Z_{ij} = \frac{Y_{ij} - \min\left(Y_{ij}, i = 1, 2,\ \ldots,\ n\right)}{\max\left(Y_{ij}, i = 1, 2,\ \ldots,\ n\right) - \min\left(Y_{ij}, i = 1, 2,\ \ldots,\ n\right)} \tag{32.2}$$

The surface roughness and kerf width should follow the lower-the-better criterion and can be given by Eq. (32.3).

$$Z_{ij} = \frac{\max\left(Y_{ij}, i = 1, 2, \ldots, n\right) - Y_{ij}}{\max\left(Y_{ij}, i = 1, 2, \ldots, n\right) - \min\left(Y_{ij}, i = 1, 2 \ldots, n\right)} \qquad (32.3)$$

32.3.2 Determination of Deviation Sequence

The deviation sequence is the absolute difference between the reference sequence and the comparability sequence after normalization. It is determined using Eq. (32.4).

$$\Delta_{oj}(k) = Y_o(k) - Y_j(k) \qquad (32.4)$$

which is the absolute difference between $Y_o(k)$ and $Y_j(k)$.

32.3.3 Determination of Grey Relational Coefficient (GRC)

The grey relational coefficient is calculated to express the relationship between the ideal and the actual normalized experimental results. The grey relational coefficient can be expressed by Eq. (32.5):

$$\Upsilon\left(Y_o(k), Y_j(k)\right) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{oj}(k) + \xi\Delta_{\max}} \qquad (32.5)$$

where $j = 1, 2, \ldots, n; k = 1, 2, \ldots, m$, n is the number of experimental data items, and m is the number of responses. $Y_o(k)$ is the reference sequence ($Y_o(k) = 1$, $k = 1$, $2, \ldots, m$); $Y_j(k)$ is the specific comparison sequence.

$$\Delta_{\min} = \frac{\min}{\forall j \varepsilon i \forall k} \frac{min}{} \left\|Y_o(k) - Y_j(k)\right\| \text{ is the smallest value of } Y_j(k)$$

$$\Delta_{\max} = \frac{\max}{\forall \mathbf{j} \varepsilon \mathbf{i} \forall \mathbf{k}} \frac{\max}{} \left\|Y_o(k) - Y_j(k)\right\| \text{ is the largest value of } Y_j(k).$$

where ξ is the distinguishing coefficient, which is defined in the range $0 \leq \xi \leq 1$. The WEDM process parameters are equally weighted in this study, and therefore, ξ is 0.5 [9].

32.3.4 Determination of Grey Relational Grade (GRG)

The grey relational grade is determined by the average of grey relational coefficient corresponding to each performance characteristic and is expressed by Eq. (32.6). The overall performance characteristic of the multiple response process depends on the calculated grey relational grade.

$$\Upsilon_j = \frac{1}{k} \sum_{i=1}^{m} \Upsilon_{ij} \tag{32.6}$$

where Υ_j is the relational grade for the jth experiment and k is the number of performance characteristics.

This approach converts a multiple response process optimization problem into a single response optimization situation with the objective function of an overall grey relational grade. Table 32.5 shows the grey relational coefficient and grey relational grade for each experiment. The higher grey relational grade reveals that the corresponding experimental result is closer to ideally normalized value. Experiment 3 has the best multiple performance characteristics among 30 experiments, because it has the highest grey relational grade shown in Table 32.4 and Fig. 32.3. The higher the value of grey relational grade, the closer the corresponding factor combination is to the optimal. A higher grey relational grade implies better product quality; therefore, on the basis of the grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined.

Figure 32.3 shows grey relational grades [16] for maximum metal removal rate, minimum surface roughness and minimum kerf width. The mean of grey relational grades is shown in Table 32.5.

32.4 Results and Discussion

Based on experimental investigations, the influence of input parameters on performance characteristics is shown in graphs of Figs. 32.4, 32.5, 32.6 and 32.7. Based on graphs, it was observed that more influencing input parameters were peak current, servo voltage, pulse on time and pulse off time.

It was observed that strong sparks are generated at high peak current (IP) and higher pulse on time (T_{on}) ensures to hold energy for longer duration of time producing high temperature, due to which more material is melted and eroded and hence MRR increases. The interelectrode gap is quite narrow by lowering the servo voltage (SV), thereby maintaining the wire much closer to the workpiece which helps in machining the peaks and minimizing the surface roughness. At lower peak current (IP) and servo voltage (SV), spark energy is less forming small-size debris which can be easily evacuated from the machining zone, thereby resulting in lower kerf width.

Table 32.4 Normalized sequence, grey relational coefficients and grey relational

Expt. No	Normalized sequence			Grey relational coefficient			Grey grade	Rank
	Kerf width (mm)	MRR (mm^3/min)	Surface roughness (μm)	Kerf width (mm)	MRR (mm^3/min)	Surface roughness (μm)		
1	0.487	0.891	0.028	0.494	0.821	0.339	0.5513	5
2	0.729	0.122	0.479	0.649	0.363	0.489	0.5003	9
3	0.729	0.000	1.000	0.649	0.333	1.000	0.6607	1
4	0.243	0.517	0.000	0.398	0.509	0.333	0.4133	28
5	0.487	0.237	0.215	0.494	0.396	0.389	0.4263	22
6	0.243	0.179	0.487	0.398	0.379	0.494	0.4237	25
7	0.243	0.465	0.223	0.398	0.483	0.392	0.4243	23
8	1.000	0.235	0.407	1.000	0.396	0.458	0.6180	2
9	0.487	0.315	0.344	0.494	0.422	0.433	0.4497	19
10	0.243	0.416	0.292	0.398	0.461	0.414	0.4243	24
11	0.729	0.816	0.011	0.649	0.731	0.336	0.5720	4
12	0.757	0.134	0.472	0.673	0.366	0.486	0.5083	8
13	0.243	0.435	0.375	0.398	0.469	0.444	0.4370	21
14	0.000	0.471	0.157	0.333	0.486	0.372	0.3970	30
15	0.243	0.407	0.261	0.398	0.458	0.404	0.4200	27
16	0.487	0.523	0.263	0.494	0.512	0.404	0.4700	13
17	0.487	0.749	0.141	0.494	0.666	0.368	0.5093	7
18	0.243	0.613	0.204	0.398	0.564	0.386	0.4493	20
19	0.487	0.304	0.503	0.494	0.418	0.502	0.4713	12
20	0.757	0.382	0.364	0.673	0.447	0.440	0.5200	6
21	0.487	0.478	0.196	0.494	0.489	0.383	0.4553	17
22	0.487	0.392	0.416	0.494	0.451	0.461	0.4687	14
23	0.243	1.000	0.138	0.398	1.000	0.367	0.5883	3
24	0.487	0.267	0.506	0.494	0.406	0.503	0.4677	15
25	0.243	0.358	0.096	0.398	0.438	0.356	0.3973	29
26	0.487	0.151	0.608	0.494	0.371	0.561	0.4753	11
27	0.487	0.215	0.588	0.494	0.389	0.548	0.4770	10
28	0.487	0.526	0.122	0.494	0.513	0.363	0.4567	16
29	0.243	0.409	0.272	0.398	0.458	0.407	0.4210	26
30	0.487	0.394	0.271	0.494	0.452	0.407	0.4510	18

The confirmation test was conducted based on optimum parameters to evaluate the performance characteristics for WEDM of Inconel 600. Table 32.5 shows the comparison of the experimental results based on the initial ($A_3B_3C_1D_3$) and optimal ($A_4B_4C_1D_2$) process parameters.

The response values obtained from the confirmation experiment are MRR = 0.2398 mm^3/min, surface roughness (SR) = 0.9 μm and kerf width =
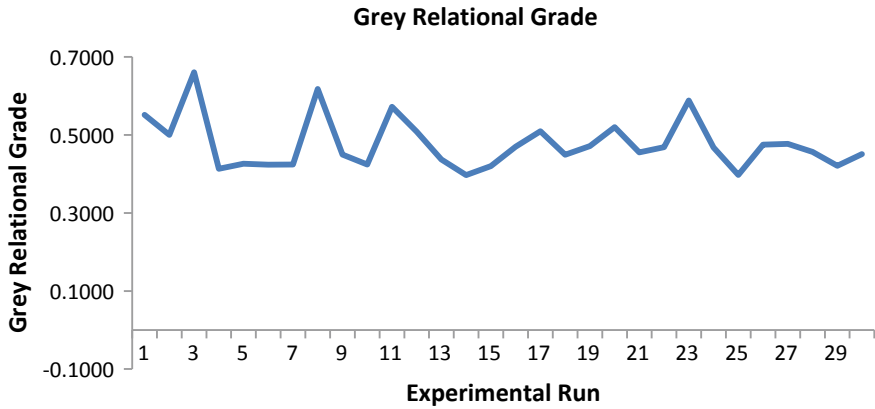
Fig. 32.3 Grey relational grade for maximum MRR, minimum Ra and minimum kerf width

Table 32.5 Optimization results of FCCD versus grey theory design

	Optimal process parameter	
	Face-centred central composite design	Grey theory grade
Level	$A_3B_3C_1D_3$	$A_4B_4C_1D_2$
Material removal rate (mm^3/min)	0.18	0.2398
Surface roughness (µm)	0.97	0.9
Kerf width (mm)	0.293	0.273
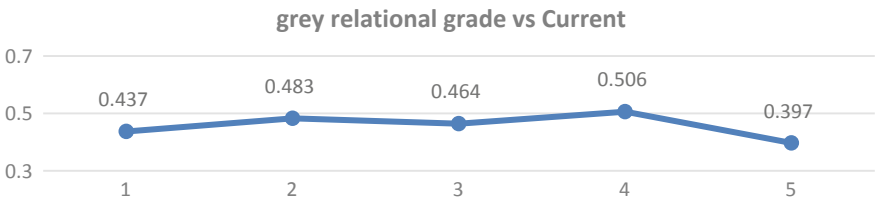
Fig. 32.4 Grey relational grade for each level of parameter (peak current)
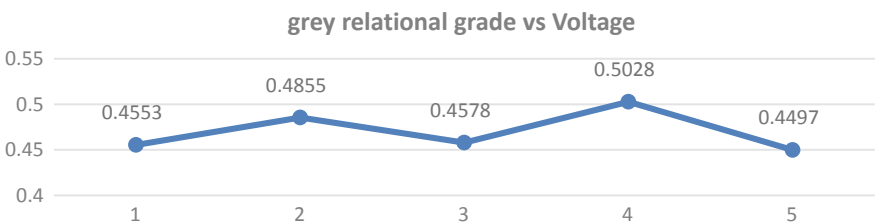
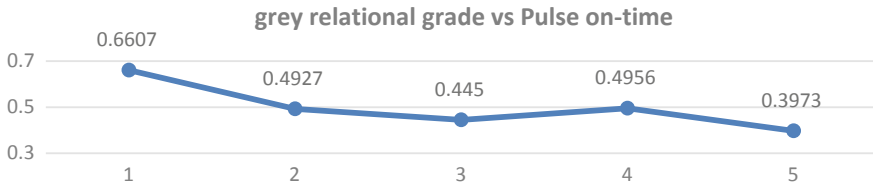**Fig. 32.5** Grey relational grade for each level of parameter (voltage)

grey relational grade vs Pulse on-time

Fig. 32.6 Grey relational grade for each level of parameter (pulse on time)

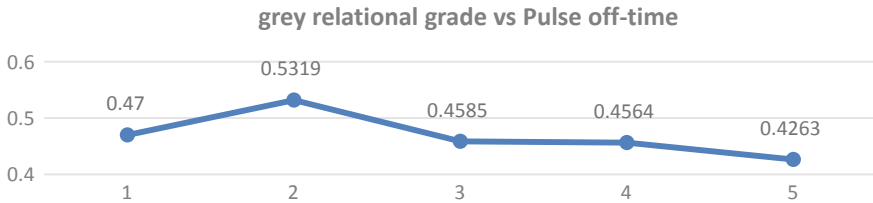grey relational grade vs Pulse off-time

Fig. 32.7 Grey relational grade for each level of a parameter (pulse off time)

0.273 mm. The material removal rate indicates an increased value from 0.18 to 0.2398 mm^3/min. The surface roughness was decreased from 0.97 to 0.9 µm, and the kerf width also decreased from 0.293 to 0.273 mm, respectively. The corresponding improvement in material removal rate, surface roughness and kerf width were 33.2, 7.22, and 6.83%, respectively.

32.5   Conclusions

In this paper, face-centred central composite design (FCCCD) and grey relational analysis were used to improve the multi-response characteristics of metal removal rate (MRR), surface roughness (SR) and kerf width (K) on the wire electrical discharge machining (WEDM) of Inconel 600 which has been reported.

   i. The optimal process parameters based on grey relational analysis for the WEDM of Inconel 600 were selected as peak current (140 A), servo voltage (65 V), pulse on time (100 µs) and pulse off time (44 µs).
  ii. Increase in pulse on time causes high discharge energy, and also increase in current causes increase of discharge energy leading to high metal removal rate.
 iii. Surface roughness was improved with decrease in servo voltage.
  iv. Based on grey relational analysis, the material removal rate improved from 0.18 to 0.2398 mm^3/min (33.2%), the surface roughness reduced from 0.97 to 0.9 µm (7.22%), and the kerf width also reduced from 0.293 to 0.273 mm (6.83%), respectively, which are positive indicators of the machining processes.

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