Optimization of Process Parameters in Wire EDM of Inconel-690 using Grey Relational Analysis

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Abstract
Wire electrical discharge machining is a non-conventional machining process which is the most preferred for the machining of hard material. Machining process is carried out with the help of spark produced in different conducting wire. In present investigation, Inconel-690 is used as work material where as brass wire with 0.25 mm diameter is used as tool material. The effect of parameters as pulse on time, pulse off time, peak current and servo voltage which are considered for the analysis of performances like kerf width, material removal rate and surface roughness. Grey relational analysis is used to optimize the output process performances in which multi response is consolidated into single grey relational grade and finds the optimum combination of parameters which provide optimum performances. Optimum performances are achieved at a combination of parameters as pulse of time (102 µs), pulse off time (63 µs), peak current (11 amp) and servo voltage (40 volt). Analysis of variance is used to calculate the percentage contribution input process parameters on grey relational grade which indicates that peak current is the most dominating parameter followed by servo voltage, pulse on time and pulse off time.

Keywords
Wire EDM, MRR, SR, KW, ANOVA, GRA

I. Introduction

As mechanical industry developed, the requirement of hard and tough material has increased. Traditional methods are not sufficient for the machining of hard material and provide various damages in machined surfaces. Wire EDM is a non-traditional method which is capable for the machining of hard material with fewer defects and provides good surfaces within the tolerances of specific requirement. Wire EDM machine consists of a main 'X-Y' worktable along with (U-V) auxiliary table and mechanism of wire feeding. Workmaterial is clamped on main worktable which moves in X and Y-axis and driven by direct current (D.C) motors. Wire is kept under tension by using wire guide which is located at opposite side of work material and continuously supplied from wire spool. Lower wire guide remains stationary and upper wire guide moves along U and V direction with respect to lower wire guide. A series of spark is produced on material with the help of wire and coolant such as de-ionized water is supplied continuously on the machining zone with the help of nozzle. To prevent the ionization of water, an ion exchange resin is used to maintain the conductivity of water. Machining is carried out with melting and vaporization of tiny particle. Researchers optimized the machining performances to get the response which provide better tolerance and surfaces for particular requirement.

Several researchers have optimized responses such as Material Removal Rate (MRR), Surface Roughness (SR) and Kerf Width (KW). Hascalyk and caydas [1] performed machining on AISI D5 tool steel using brass wire by varying the wire speed, pulse duration, open circuit voltage and dielectric fluid pressure. It was found that hardness was not affected by wire speed while increase in pulse duration and open circuit voltage resulted in large surface roughness. Jangra et al. [2] used WC-Co composite for the machining using zinc coated brass by varying wire tension, pulse on time, pulse off time, taper angle, dielectric flow rate and peak current. It was found that taper angle, pulse on time and pulse off time have the highest impact on MRR and SR. Mevada [3] used Inconel 600 as work material of two plates, each of size 150 x 300 x 10 mm and three different wires namely brass of 0.25 mm, zinc coated brass of 0.25 mm and molybdenum of 0.18 mm were used as wire material. MRR achieved with brass wire was higher than molybdenum and zinc coated brass wire while molybdenum wire provided less roughness than brass and zinc coated brass wire. Shah et al. [4] performed experimental work on Inconel 600 using molybdenum wire. Pulse on time has the highest effect on material removal rate where as wire speed has the least effect on material removal rate.

Kumar et al. [5] performed machining operation on tool steel EN 24 using brass by varying pulse on time, pulse off time, spark gap set voltage and peak current. It was found that pulse on time (48.24 %) has the highest effect on MRR. Nourbakhsh et al. [6] used titanium alloy as work material and two types of wire namely high speed brass and zinc coated brass were used as wire material. It was found that surface roughness increased with increase in pulse width and peak current. Surface roughness decreased with increase in wire tension. Material removal rate was higher in case of zinc coated brass wire as compared to high speed brass wire. Durairaj et al. [7] performed experimental work on Inconel 800 using brass wire by varying pulse on time, pulse off time, wire feed and gap voltage. It was found that pulse on time has the highest effect on surface roughness while dielectric fluid pressure,wire tension, wire speed and cutting length were considered as fixed parameters.

In the present paper, Inconel 690 has been machined using brass wire to optimize material removal rate, kerf width and surface roughness by varying the parameters like pulse on time, pulse off time, peak current and servo voltage.

II. Work Material

Inconel 690 was used as work material in present investigation and its chemical composition of is shown in Table 1.

Table 1: Chemical Composition of Inconel 690

INCONEL 690	
Elements	Specifications (%)
Nickel	57.74
Chromium	28.72
Aluminium	0.96
Titanium	0.27
Iron	8.70
Silicon	0.66

III. Experimental Setup

In the current experimental work, all experiments were performed on an ELECTRONICA Wire EDM machine. Work material with dimension 100 mm x 150 mm x 10 mm was used and specimens were cut into sizes of 20 mm x 10 mm x 10 mm with the help of brass wire. The range of parameters for present investigation was selected as pulse on time (102-110 µs), pulse off time (57-63 µs), peak current (10-12 Amp) and servo voltage (40-80 Volt). Minitab 17 Software was used for orthogonal array design for experiment shown in Table 2.

Table 2: Design of L9 Orthogonal Array

S. No	Pulse on time	Pulse off time	Peak Current	Servo Voltage
1	102	57	10	40
2	102	60	11	60
3	102	63	12	80
4	106	57	11	80
5	106	60	12	40
6	106	63	10	60
7	110	57	12	60
8	110	60	10	80
9	110	63	11	40

IV. Result and Discussion

Experiments were executed at given orthogonal array and experimental data for kerf width, MRR and SR were collected as shown in Table 3 which was optimized using grey relational analysis. Grey Relational Analysis (GRA) is a multi objective optimization technique into single optimal process performance. It is a normalization technique in which process performances are normalized between 0 and 1. For some process performance optimization such as MRR, "larger-the-better" whereas for some process performance optimization such as Kerf width and surface roughness, "smaller-the-better" are used. In GRA, these process performances are optimized into single process performance optimization and "larger-the-better" is used for single optimized performances. The step by step GRA process is described below for single optimal parameter combination which provides optimal performances.

Table 3: Final Measurement Data of KW, MRR and SR

S. No	Kerf Width (mm)	MRR (mm^3/min)	SR (µm)
1	0.5174	0.3832	0.85
2	0.4293	1.9513	0.67
3	0.4159	1.9344	0.75
4	0.4476	2.2380	0.85
5	0.4253	2.8353	0.94
6	0.6173	0.3919	1.11
7	0.4418	1.353	0.84
8	0.5423	0.32397	0.92
9	0.4331	3.4648	0.62

A. Normalization of Experimental Results of Process Performance

The measured experimental values of KW, MRR and SR are normalized between 0 and 1. This procedure is called grey relational normalization. Process performances having quality characteristic "larger-the-better" are normalized by using the equation (1)

$$x_i(k) = \frac{max\ y_i(k) - y_i(k)}{max\ y_i(k) - min\ y_i(k)} \quad (1)$$

The process performances having quality characteristic "smaller-the-better" are normalized by using the equation (2)

$$x_i(k) = \frac{max\ y_i(k) - y_i(k)}{max\ y_i(k) - min\ y_i(k)} \quad (2)$$

Here $x_i(k)$ is the value obtained after grey relational normalization, $y_i(k)$ is the response value of kth response, and max $y_i(k)$ is the largest value of for kth response and min $y_i(k)$ is the minimum response for kth response. Sequence k is (1, 2, 3... 9), k is used for the responses.

Normalization is done between 0 and 1 for KW, MRR and SR which is shown in Table 4. Here smaller-the-better normalization equation is used for KW and SR. Larger-the-better normalization equation is used for MRR.

Table 4: Data Pre-Normalization for KW, MRR and SR

Exp No.	Data Pre-Normalization		
	KW	MRR	SR
Reference Sequence	1.0000	1.0000	1.0000
1	0.4960	0.0189	0.5306
2	0.9334	0.5181	0.8979
3	1.0000	0.5128	0.7346
4	0.8426	0.6094	0.5306
5	0.9533	0.7995	0.3469
6	0.0000	0.0217	0.0000
7	0.8714	0.3296	0.5510
8	0.3723	0.0000	0.3877
9	0.9145	1.0000	1.0000

B. Calculation of Deviation Sequence

To calculate grey relation coefficient, first calculate deviation sequence using Eq (3) as shown in Table 5.

$$\Delta_{0i}(k) = |x_0(k) - x_i(k)| \quad (3)$$

The deviation sequences $\Delta_0(i)$, $\Delta_{max}(k)$ and $\Delta_{min}(k)$ for i=1 to 9 and k=1 to 3 can be calculated as follows:

$\Delta_{01}(1) = |x_0(1) - x_1(1)| = |1.0000 - 0.4960| = 0.5040$

$\Delta_{01}(k) = |x_0(2) - x_1(2)| = |1.0000 - 0.0189| = 0.9811$

$\Delta_{01}(k) = |x_0(3) - x_1(3)| = |1.0000 - 0.5306| = 0.4694$

Table 5: Deviation Sequences

Exp No.	Δ_{0i} (1)	Δ_{0i} (2)	Δ_{0i} (3)
1	0.5040	0.9811	0.4694
2	0.0666	0.4819	0.1021
3	0.0000	0.4872	0.2654
4	0.1574	0.3906	0.4694
5	0.0467	0.2005	0.6531
6	1.0000	0.9783	1.0000
7	0.1286	0.6704	0.4490
8	0.6277	1.0000	0.6123
9	0.0855	0.0000	0.0000

C. Calculation of Grey Relational Coefficient and Grey Relational Grade

Grey relational coefficient is given by using equation (4):

$$\xi_i(k) = \frac{\Delta min + \psi\, \Delta max}{\Delta_{0i}(k) + \psi\, \Delta max} \quad (4)$$

$$\Delta min = \min_{i \in I} \min_{k} |x_0(k) - x_i(k)| = \Delta_{03}(1) = \Delta_{09}(2) = \Delta_{09}(3) = 0.0000$$

$$\Delta max = \max_{i \in I} \max_{k} |x_0(k) - x_i(k)| = \Delta_{06}(1) = \Delta_{08}(2) = \Delta_{06}(3) = 1.0000$$

Where $\Delta_{0i}(k)$ is the value of deviation sequence of $x_i(k)$ and the comparability sequence ψ = identification coefficient lies between 0 and 1. Grey relational coefficient is calculated by selecting proper distinguishing coefficient generally $\psi = 1$ is accepted. In the present study $\psi = 1$ is considered.

Grey relational grade is calculated by using equation (5):

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (5)$$

Where n is the number of process responses, is the grey relational grade for the kth experiment.

The distinguishing coefficients were substituted for grey relational coefficient in Equation (3). By applying Equation (4) and Equation (5), grey relational coefficient and grade for L9 orthogonal array are tabulated in Table 6.

Table 6: Calculation of Grey relational Co-efficient & Grey relational grade

Exp No.	Grey Relation Coefficents			Grey Relational Grade	Orders
	KW [ξ_i (1)]	MRR [ξ_i (2)]	SR [ξ_i (3)]		
1	0.6649	0.5048	0.6805	0.6167	7
2	0.9376	0.6748	0.9073	0.8399	2
3	1.0000	0.6724	0.7903	0.8209	3
4	0.8640	0.7191	0.6805	0.7545	5
5	0.9553	0.8329	0.6049	0.7977	4
6	0.5000	0.5054	0.5000	0.5018	9
7	0.8860	0.5986	0.6901	0.7249	6
8	0.6143	0.5000	0.6202	0.5781	8
9	0.9212	1.0000	1.0000	0.9737	1

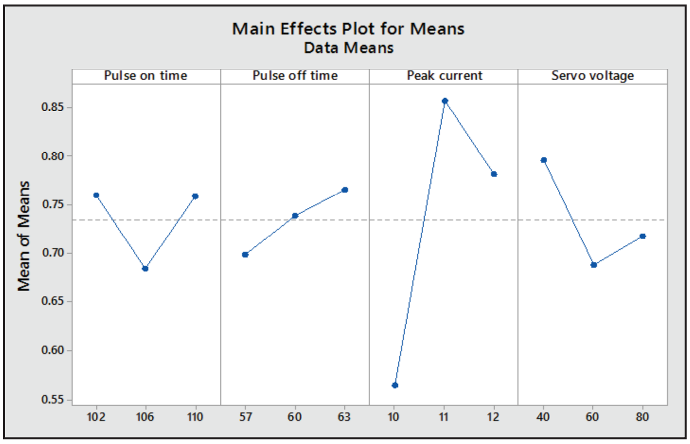

Fig. 1: Graph of Grey Relational Grade V/S Inputs Process Parameters

Optimal level for each input process parameter is indicated by larger grey relational grade as shown in fig. 1 which was achieved at pulse on time (102 µs), pulse off time (63 µs), peak current (11 Amp) and servo voltage (40 volt).

D. Analysis of Variance for Grey Relational Grade

In the present work, Response and ANOVA Table for grey relational grade are shown in Table 7 and Table 8 respectively. Result shows the percentage contribution of each input process parameters on grey relational grade. The percentage contribution of parameters were pulse on time of 6.40%, pulse off time of 3.93%, peak current of 79%, and servo voltage of 10.67%.

Table 7: Response Table for Grey Relational Grade

Level	Pulse on time	Pulse off time	Peak Current	Servo Voltage
1	0.7592	0.6987	0.5655	0.7960
2	0.6847	0.7386	0.8560	0.6889
3	0.7589	0.7655	0.7812	0.7178
Delta	0.0745	0.0668	0.2905	0.1072
Rank	3	4	1	2

Table 8: ANOVA for Grey Relational Grade

Source	Degree of Freedom	Sum of Square	Variance	Contribution (%)
Pulse on time	2	0.011061	0.005530	6.40
Pulse off time	2	0.006771	0.003385	3.93
Peak Current	2	0.136493	0.068247	79
Servo Voltage	2	0.018439	0.009220	10.67
Total	8	0.172764		100

E. Confirmation Test for Multi-response Optimization

Confirmation test was performed to check the values predicated by minitab 17 software at optimal level values shown in Table 9. Optimal performances were achieved at 102 µs of pulse on time, 63 µs of pulse off time, 11 amp of peak current and 40 volt of servo voltage and it gives KW of 0.4069 mm, MRR of 3.2552 mm^3/ min and SR of 0.55 µm with error in KW of 1.93%, MRR of 2.56% and SR of 3.99 %.

Table 9: Confirmation Experiment for KW, MRR and SR

Condition Description	Predicated Value	Experimental Value	% Error
LEVEL	102-63-11-40	102-63-11-40	
KW	0.4149 mm	0.4069 mm	1.93
MRR	3.17183 mm^3/min	3.2552 mm^3/min	2.56
SR	0.58333 µm	0.56 µm	3.99

V. Conclusion

Experimental work was performed on Inconel 690 work material using brass wire to optimize machining performances like kerf width, material removal rate and surface roughness and following conclusions were achieved:

1. Peak current was the most dominating parameter followed by servo voltage, pulse on time and pulse off time.
2. Optimal performances (kerf width, material removal rate and surface roughness) were obtained at a combination of parameter as pulse on time (102 μs), pulse off time (63 μs), peak current (11 A) and servo voltage (40 V).

Abbrevation

MRR - Material Removal Rate
SR - Surface Roughness
KW - Kerf Width
GRA - Grey Relational Analysis

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