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Multi-Objective Optimization using Taguchi Based Grey Relational Analysis for Wire EDM of Inconel 625

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Abstract—*This paper investigates the feasibility of applying WEDM process for Inconel 625. The selection of optimal parametric settings during WEDM is great concern in manufacturing sector, these days. Hence, an attempt has been made to study the effects of process parameters on the performance characteristics. The process parameters includes the Peak current (IP), pulse on time (Ton), wire tension WT and wire feed rate WF, each having three levels. The material removal rate (MRR-mm^3/min) and surface roughness (SR-μm) were considered as responses. The experiments have been performed using Taguchi's L9 (3^4) orthogonal array. The optimal parametric settings were determined by the grey relational grade (GRG) obtained through grey relational analysis (GRA). The results were analyzed using an effective approach namely Taguchi based grey relational analysis (TGRA). It is observed that through TGRA; the multi-objective optimization can be greatly simplified. Analyzed results have shown that pulse on time is most effective controllable factor followed by peak current, wire feed rate and wire tension.*

Keywords*: Super alloys, WEDM, TGRA, Multi-objective parametric optimization, Performance measures.*

1. INTRODUCTION

The manufacturing industries faces challenges during machining of advance material hiving complex shape geometries, high precision and high surface finish requirement. Wire electrical discharge machining is one of the widely used non-conventional machining techniques. WEDM is a thermoelectric machining process used for machining advances materials such as composites, ceramics, inter metallic materials and super alloys.[1]

The WEDM process makes use of electrical energy generating a channel of plasma between the cathode and anode [2]. Wire cut- EDM is low cutting force process and used when low residual stress are desired during machining of materials hence little change occurs in the mechanical properties of materials.[3] This process is widely used in manufacturing of cam wheels, special gears, stators for stepper motors, various press tools, dies and similar intricate parts and also used to make much precised equipments in prosthetics, biomedical and aerospace applica-tions.[4-5] In this work, The selection of optimum machining process parameter in WEDM is an important consideration. Gray relational analysis is applied to optimize the process parameters having multi-response through grey relational grade.

2. LITERATURE REVIEW

In WEDM, It is extremely significant to select machining parameter for achieving optimal machining performance. Aggarwal et al. [10] has recommended a parametric modeling and optimization for wire electrical discharge machining of Inconel 718 using response surface methodology and concluded that cutting rate increases with an increase in pulse-on time, and decreases with the increase in pulse-off time. The pulse-on time has a larger effect on the cutting rate at low pulse-off time than at high pulse off time. Ikram et al. [11] explained the method of optimization of WEDM process parameters using Taguchi method. It has been shown that pulse on-time has more significant factors for MRR and kerf width. Boopathi et al. [12] performed a study on the parameter optimization of near-dry wire-cut electrical discharge machining using multi objective evolutionary algorithm. Results of their experiments indicated that The pulse-on time, discharge current and gap voltage are the significant parameters in order to increase the metal-cutting speed and to improve the surface finish in the near-dry WEDM. While increasing the air-mist pressure up to 5 bar, the MRR and surface finish values are improved.

3. EXPERIMENTAL PROCEDURE

A series of experimental trials have been conducted as par grey relational analysis (GRA). The details about the work material, experimental set-up and measuring apparatus, selection of process parameters and their range, design of experiment have been explained in the following section.

3.1 Work material

A plate of Inconel 625 having dimension of 150 x 80 x 8mm has been used in the process study. Inconel 625 have tensile strength of 1103 MPa, compressive strength of 2200 MPa and hardness value of 120 HRC . It has excellent oxidation and scaling resistance at temperatures up to 1093 °C. Due to high fatigue resistance, high corrosion resistance, high temperature strength, high degree of formability with better weld ability, Inconel 625 is widely used in chemical processing, aerospace and marine engineering, pollution-control equipment and nuclear reactor applications etc. Inconel 625 is basically an alloy of nickel-chromium and molybdenum with the following Composition:

Table 1: Work material Composition

C%	Ni %	Cr %	Mo %	Nb %	Co %	Mn %	Si %	P%	S%	Ti %
0.087	64.3	20.57	8.37	3.25	0.40	0.36	0.25	0.014	0.012	0.15

3.2 Wire Material

A thin wire is used as tool electrode in wire electrical discharge machining (WEDM). The wire electrode is required to have a sufficient tensile strength with uniform diameter and free from kink or twist. In the present study, the brass wire having diameter of 0.25 mm is chosen as tool wire electrode material. Brass being an alloy of copper and zinc that has good resistance to atmospheric corrosion and is easily fabricated by processes like spinning, forming, machining and casting.

3.3 Experimental set-up

The experiments were performed on an ELEKTRA SPRINTCUT 734 wire-cut EDM machine of ELECTRONICA MACHINE TOOL Ltd. The experimental aim was to study the effect of several controllable process parameters on metal removal rate and surface finish taken as performance measures. Wire was connected to negative polarity whereas the work piece at positive polarity. The sparks will generate between two closely spaced electrodes under the influence of dielectric liquid. De-ionized Water is used as dielectric in WEDM having low viscosity and rapid cooling rate.

The high-energy density erodes material from both the wire and workpiece by local melting and vaporization. The de-ionized water is continuously flushed through the gap between wire and workpiece hence remove the debris produced by the erosion action. The cutting rate is displayed digitally on the control panel of the machine in mm/min which is utilized to calculate the MRR.

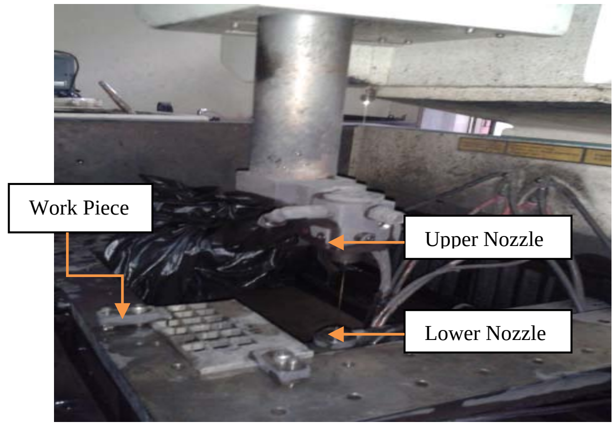

Fig. 1: Elektra sprintcut 734 wire-cut EDM

3.4 Selection of process parameters:

For the present experimental work the four process parameters i.e. peak current, pulse on-time, wire tension, wire feed rate, each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect true behavior of output parameters of study. The levels of the individual process parameters are given in Table 2.

Table 2: Process Parameters and their levels have been decided on the basis of preliminary runs

Factor	Name	Levels		
A	Peak current (A)	60	100	140
B	Pulse on time(µs)	108	118	128
C	Wire tension(WT)	8	9	10
D	Wire feed rate (WF)	6	8	10

Table 3: Experimental conditions

Parameter	Description/ Value
Wire material	Brass
Wire diameter	0.25 mm
Workpiece material	Inconel 625
Workpiece hardness	120 HRC
Pulse peak voltage	110 V DC
Dielectric fluid	De-ionized water
Machining width	15 mm
Machining height	15 mm

4. DESIGN OF EXPERIMENT (DOE):

Design of experiments (DOE) is a systematic and precised approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible and supportable engineering conclusions. The experiments utilized L9 orthogonal array to study the effect of process parameters.

The number of treatment condition is equal to the number of row in orthogonal array and must be equal to or greater than the degree of freedom of different parameters considered. As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degree of freedom (DOF). There are total of 8 degree of freedom for four process parameters namely peak current, pulse-on time, wire tension and wire feed rate selected in present study. The total degree of freedom for the four factors is 8. So, the array selected fulfils the criterion for selection of array. The result has been analyzed based on Grey based Taguchi method (TGRA).

5. EXPERIMENTAL RESULTS AND DISCUSSIONS:

In this experimental work, material removal rate is calculated as:

MRR= V_c x b x h mm^3/min

The above equation after Rao et al.(2010) [9]

Where: V_c = Cutting speed in millimeters per minute

b= Width of cut in millimeter

h= Height of workpiece in mm

The surface roughness is measured with Taylor Hobson Surtroni 25.

Fig. 2: Work piece after wire EDM

Table 4: Experimental layout using an L9 orthogonal array and experimental results

Run	Peak Current Ip(A)	Pulse-ON time Ton (μs)	Wire Tension WT (g)	Wire feed rate, WFR (m/min)	Performance Measures					
					MRR (mm3/min)	MRR (mm3/min)	MRR (mm3/min)	SR(μs)	SR(μs)	SR(μs)
1	60	108	8	6	134.4	136.8	140.4	0.86	0.90	0.96
2	60	118	9	8	225.6	229.2	231.6	1.52	1.56	1.60
3	60	128	10	10	232.8	235.2	236.4	1.64	1.68	1.71
4	100	108	9	10	141.6	144	147.6	0.97	0.99	1.04
5	100	118	10	6	286.8	289.2	291.6	1.66	1.70	1.76
6	100	128	8	8	351.6	354	357.6	1.75	1.77	1.80
7	140	108	10	8	154.8	159.6	163.2	1.19	1.24	1.28
8	140	118	8	10	292.8	294	297.6	2.00	2.14	2.19
9	140	128	9	6	393.6	397.2	402	2.84	2.89	2.97

5.1 Determine optimal process parameter:

5.1.1 Normalizing the experiment data:

In grey relational analysis, experimental data, i.e., measured features of quality characteristics, are first normalized range from zero to one. This process is known as gray relational generation. In Grey relational generation, normalized result of Surface finish, $x_i(k)$, should follow smaller-the-better (SB) criterion which can be expressed as : [7]

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

The normalized result of metal removal rate (MRR), $x_i(k)$, should follow larger-the-better (LB) criterion which can be expressed as :

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

Where $x_i(k)$ is the value after the gray relational generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, and max $y_i(k)$ is the largest value of $y_i(k)$ for kth response. An ideal sequence is x_0 (k) (k = 1, 2, 3,….9) for the response.

Table 5: Normalization of the experimental result for each performance measure: MRR and SR

Exp. run	Data normalizing					
	MRR			SR		
	1	1	1	1	1	1
1	1.0000	1.0000	1.0000	0.4737	0.4737	0.4737
2	0.718	0.7172	0.7208	0.5745	0.5739	0.5690
3	0.7033	0.7043	0.7104	0.5976	0.5968	0.5894
4	0.9701	0.9702	0.9703	0.4880	0.4852	0.4838
5	0.6049	0.6060	0.6089	0.6016	0.6008	0.5992
6	0.5178	0.5190	0.5201	0.6205	0.6153	0.6073
7	0.9196	0.9113	0.9117	0.5192	0.5205	0.5170
8	0.5956	o.5985	0.5996	0.6796	0.7048	0.6987
9	0.4737	0.4737	0.4737	1.0000	1.0000	1.0000

5.1.2 Grey relational coefficient

Based on normalized experimental data, grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. The gray relational coefficient, ξ_{ij}, can be expressed as [4]

$$\zeta_{ij} = \frac{\min_i \min_j \left|x_j^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_j^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|}$$

5.1.3 Determination of grey relational grade

Grey relational grade is calculated by averaging the relational coefficient corresponding to each performance measures and expressed as: [5]

$$r_i = \frac{1}{m}\sum_{j=1}^{m} \xi_i j$$

Thus by applying above equation, all grey relational grade can be computed, which provide an alternative ranking. Here the higher value determines a better alternative thus the higher GRG represents that the corresponding S/N ratio is closer to the ideal normalized value. The GRG obtained for each experimental run and the ranking order of the experiment is shown in table. It is seen that experimental run 1 has the best multiple performance characteristics among 8 runs performed and having highest value of GRG and is optimal. It is followed by experiment no.9 and 4, being ranked as second and third, respectively.

Table 6: GRG for each experimental run

Exp run	GRG	Order
1	0.7368	1
2	0.6457	7
3	0.6503	5
4	0.7279	3
5	0.6036	8
6	0.5667	9
7	0.7166	4
8	0.6462	6
9	0.7350	2

5.1.4 Construction of Response table for grey relational grade (GRG)

The effect of each process parameter of Inconel 625 on the grey relational grade at different level can be separated out because the experimental design is L9 orthogonal array. The mean of gray relational grade for the peak current (I_p) at level 1,2 and 3 is calculated by averaging the grey relational grade for experiments 1 to 3, 4 to 6, 7 to 9, respectively. Similarly, it is calculated for the respected level for Pulse on time, wire feed rate, wire tension. The difference between the maximum and minimum value of GRG are calculated and ranked accordingly.

Table 7: Response table for grey relational grade

Levels	Ip(A)	Ton (µs)	WF(g)	WT(m/min)
1	0.6776	0.7271	0.6499	0.6636
2	0.6327	0.6318	0.7035	0.6418
3	0.70	0.6513	0.6568	0.6195
Delta	0.0673	0.0953	0.0536	0.0441
Rank	2	1	3	4

As accordingly ranked in table 7, pulse on time has the strongest effect on the multi-performance characteristics and the greatest GRG value gives the optimal parametric setting like peak current (Level 3), pulse on time (Level 1), wire feed rate (Level 2), wire tension (Level 1) respectively **Ip_3, T_{on1}, WF_2, WT_1** which gives better result of performance characteristics.

Main effect plot for grey relational grade (GRG)

The main effect plot (responses graph) based on grey relational grade where the mid line indicates the value of total mean of the grey relational grade. From all below subplots, it has been observed that optimum parametric setting for higher value is Ip_3, T_{on1}, WF_2, WT_1.

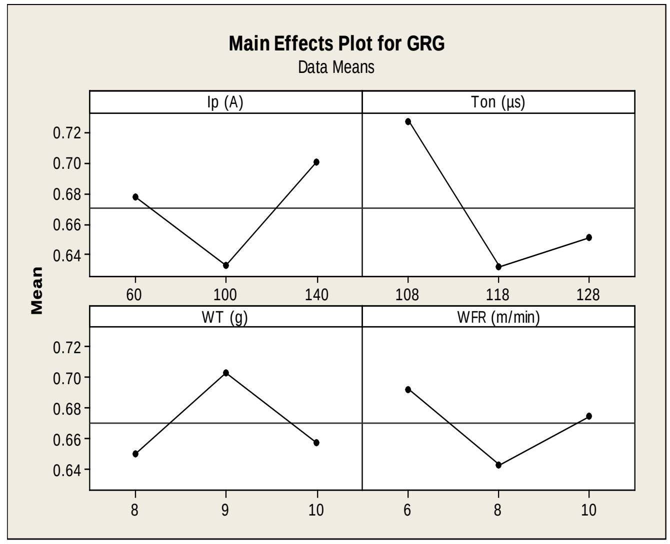

Fig. 3: Main effect plot for GRG

Trend analysis plot of GRG for linear trend model

Trend analysis plot shows the original data, the fitted trend line and forecasts. The session window output also displays the fitted trend equation and three measures of accuracy of the fitted model: MAPE, MAD and MSD for each of forecasting and smoothing methods.

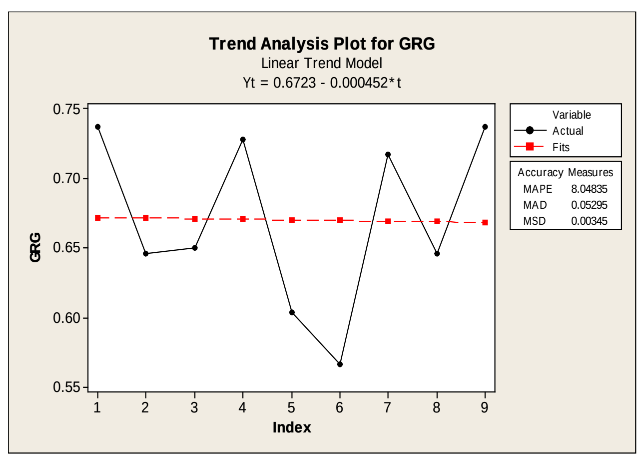

Fig.4: Trend analysis plot for GRG

Surface plot

The surface plot is used to plot points and surfaces in three dimensions. When the surface plot is used as a separate platform, the point are linked to the data table surface plot is built using 3D scene commend. Surface plot are basically three-dimensional plot in X, Y and Z direction in which the effect of two input variable are analyzed against one performance characteristic. The input process parameters are chosen along X axis and Y axis, and response is taken along Z axis.

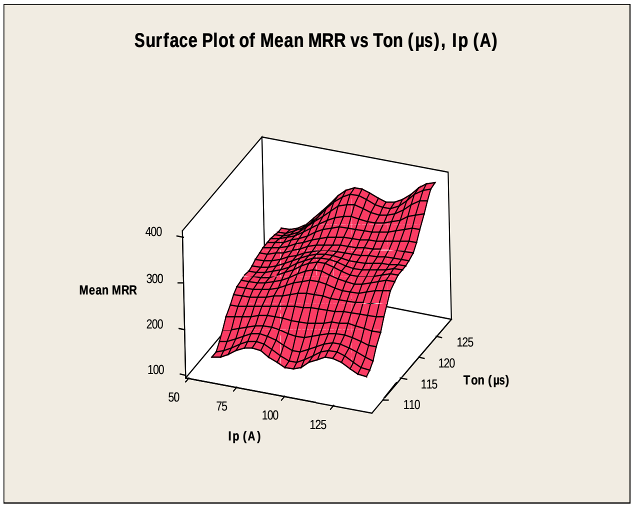

Fig. 5: Surface plot of mean MRR vs. peak current, pulse on time

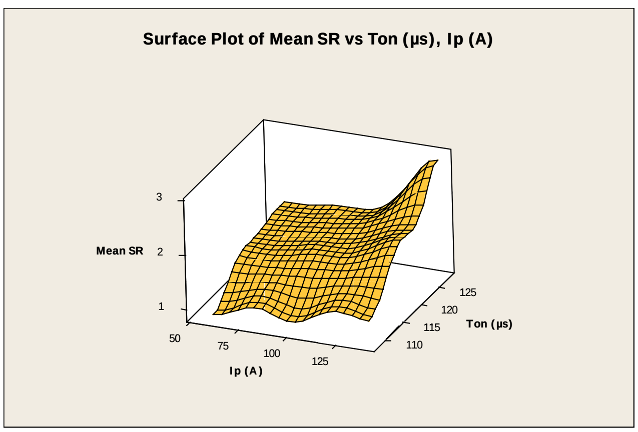

Fig. 6: Surface plot of mean SR vs peak current and pulse on time

6. CONCLUSION

Research conclusion represents that the pulse on time has the most controllable effective factor for MRR and SR followed by peak current, wire feed rate and wire tension. When pulse on time and peak current increases, the MRR increases. As the wire feed rate increases, surface finish also increases. This is $\mathbf{Ip_3}$, $\mathbf{T_{on1}}$, $\mathbf{WF_2}$, $\mathbf{WT_1}$ are optimal setting to obtain better result of performance characteristics.

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