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PROCESS-PARAMETER OPTIMIZATION OF WEDM WITH INCONEL 825 ALLOY USING GRA

OPTIMIZACIJA PROCESNIH PARAMETROV ŽIČNE EROZIJE ZLITINE INCONEL 825 Z UPORABO SIVE RELACIJSKE ANALIZE

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The process-parameter optimization of a wire electrical discharge machining (WEDM) process has been performed with an Inconel 825 alloy during taper profile machining. The input parameters have been considered at three different levels and the number of experiments to be performed was decided using Taguchi's Design of experiment (DOE). The output performances such as material removal rate (*MRR*), Surface roughness (SR) and taper error (TE) were considered simultaneously for the optimization process. The experimental results were analysed using Grey relational analysis (GRA) and the best experimental trial was identified based on ranking. The influence of the input parameters was analysed using the ANOVA technique. The regression equations to predict the output responses were formed using the experimental results and the correlation between the experimental and regression equation results.

Keywords: Inconel 825 alloy, grey relational analysis, design of experiments, regression equation

Avtorji članka so izvedli optimizacijo procesnih parametrov žične erozije (WEDM) zlitine Inconel 825 med profilno mehansko obdelavo. Vhodne parametre so ocenjevali na treh različnih nivojih in s Taguchijevim dizajnom eksperimentov (DOE) so določili število izvedenih eksperimentov. Izhodne lastnosti kot so: hitrost odvzema materiala (*MRR*), površinska hrapavost (SR) in napaka ostrine roba (TE); so ocenjevali istočasno z optimiziranjem procesa. Eksperimentalne rezultate so analizirali z uporabo sive relacijske analize (GRA) in najboljši eksperimentalni preizkusi so bili izbrani na osnovi razvrščanja. Vpliv vhodnih parametrov so analizirali s tehniko ANOVA (analiza Variance). Izdelali so regresijske enačbe za napoved odgovarjajočih izhodnih parametrov na osnovi eksperimentalnih rezultatov in podana je bila korelacija med eksperimentalnimi rezultati in rezultati regresijskih enačb.

Ključne besede: zlitina Inconel 825, siva relacijska analiza, načrtovanje eksperimentov, regresijska enačba

1 INTRODUCTION

Machining of components is inevitable in the manufacturing sectors. The development of newer materials demands a non-traditional machining process owing to the higher hardness and poor machinability of more recent materials. A few of the non-traditional machining processes commonly employed are: abrasive jet machining, electrical discharge machining, laser beam machining and electron beam machining. It is required to economically machine the components using non-traditional machining processes as the processing cost is higher than conventional machining processes. The quality achieved in non-traditional machining processes is based on the process parameters. Hence, the use of optimal process parameters is essential to achieve desirable output responses. Some of the output responses related to machining are the material removal rate (*MRR*) and surface roughness (SR).

In this research, the machining-parameter optimization has been carried out for wire electrical discharge machining (WEDM). The Inconel 825 material, which is corrosive resistant and complicated to machine using other machining processes, has been chosen for optimizing the process parameters. However, the WEDM process is employed for the machining of various components; the profile machining is often used to produce slant surfaces, in particular, die-making processes. The input machining parameters of WEDM such as pulse on time, Pulse off time, wire tension, and taper angle are considered for the optimization process. In profile machining, the taper error (TE) developed due to wire tension is commonly observed. The output responses such as *MRR*, SR and TE have been considered for optimization.

To study the technology in WEDM process and optimization, the kinds of literature published in leading journals have been collected, and the salient features of some of the published works of literature are briefed. Many research works have already been carried out on different materials with the WEDM process to obtain better, accurate results. H. R. Tonday and H.M. Tigga evaluated the performance characteristics of wire cut electrical discharge machining on output responses such as machining time and surface roughness for Inconel 718 by Taguchi method, analysis of variance and response surface methodology.

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It was found that the pulse-on time was the most significant parameter influencing the output responses.[1] V. Kavimani et al.[9] investigated the impact of WEDM input parameters on the output responses *MRR* and the surface roughness for magnesium metal-matrix composites. They have utilized Taguchi-based grey relational analysis to get the best combination of input parameters.[2] Rahul, Savrav Datta et al. determined the material removal efficiency and optimal parameter settings for three different grades of materials: Inconel 601, Inconel 625 and Inconel 718. They have used the satisfaction function approach integrated with the Taguchi method to determine the optimal parameter settings. They also studied the surface morphology along with the topographical features of electric discharge machining. The effects of peak discharge current on various performance measures were graphically represented.[3] Rahul Savrav Datta et al.[3] studied the effect of cryogenic treatment of tool/workpiece material to evaluate the ease of machining of an electric discharge machining process on Inconel 825 for the output responses such as *MRR*, roughness average, surface crack intensity and white layer thickness. In this study, the authors considered three different tool-workpiece combinations for the analysis such as Normal Tool Normal workpiece, Cryogenically treated tool normal workpiece, Normal tool cryogenically treated workpiece and the morphology of the machined surface was studied with a scanning electron microscope.[4] R. K. Fard et al.[5] experimentally investigated the effect of pulse-on time, pulse-off time, gap voltage, discharge current, wire speed wire feed on the output responses cutting velocity and surface roughness using dry wire electrical discharge machining. ANOVA was used to find the significant factors. An artificial Bee colony algorithm associated with adaptive neuro-fuzzy Inference system was utilized for getting the required output responses. It was derived from ANOVA that the pulse-on time and discharge current were the significant parameters for cutting velocity and surface roughness.[5] Soundararajan et al. investigated the effect of WEDM process parameters such as pulse-on time, pulse-off time, peak current on the material removal rate and surface roughness for the squeeze cast A413 alloy using the desirability function approach. The significant parameters were estimated by ANOVA. Mathematical models were also developed for the study.[6] K. Mouralova et al. analysed the surface morphology and topography for wire electric discharge machined pure aluminium. These were found by scanning electron microscope and included with a local analysis of chemical composition with EDX and a profilometer. The study helped to find the optimum settings of the machining parameters for the quality machined surface and narrow kerf width.[7]

Mouralova et al. quantitatively and qualitatively evaluated the craters formed on the surface of 16MnCr5 steel material. Diffusion subsurface damages were studied by applying metallography to the cross-sections of the microscopic slides. The local point EDX microanalysis was carried out to explore the diffusion effects on machined surfaces and the cross-sections.[8] V. Kavimani et al.[9] adopted Taguchi-based grey relational analysis to investigate the wire electrical discharge machining parameters on a powder metallurgy route fabricated magnesium metal-matrix composites reinforced with reduce grapheme oxide. It was concluded from the ANOVA that the weight percentage and pulse-on time are the factors influencing the material removal rate and the surface roughness. It was found that the experimental values were augmented well within the regression model.[9] Himadri Majumder et al. predicted the wire electrical discharge machining responses like surface roughness and microhardness for the shape-memory alloy nitinol by considering the input parameters such as pulse on, discharge current, wire feed, wire tension and flushing pressure. The grid search method, GRNN model, multi-criteria decision-making approach, Fuzzy logic coupled with MOORA was applied for optimizing the correlated responses.[10] Abhijit Saha et al. proposed a novel grey relational analysis combined with principal component analysis to optimize the material removal rate and surface roughness of a nanostructured hard facing material in wire electrical discharge machining. From the grey relational analysis, it was found that the discharge pulse time was the most significant parameter for brass and zinc-coated brass wires. It was recommended to use zinc-coated brass wires for machining hard facing materials.[11] Mao-Yong LIN et al. had optimized the micro-milling electrical discharge machining (EDM) process parameters to improve the performance characteristics such as low electrode wear, high material removal rate and short working gap for Inconel 718 material using the grey Taguchi method.[12] Selvakumar et al. analysed the optimal machining parameters to machine Al5083 in WEDM. The surface roughness and cutting speed were the output responses for the input parameters of pulse-on time, pulse-off time, peak current and wire tension. The influence of input parameters was determined based on the signal-to-noise (*S/N*) ratio. The Taguchi method was used to find the optimal values of the responses.[13] Priyaranjan Sharma et al. investigated the effect of wire diameter on the performance characteristics of WEDM. The parameters such as cutting speed, surface roughness, surface topography, recast layer formation, microhardness, and microstructural and metallurgical changes and their effects were reported. From the study, it was recommended to have a larger diameter wire to improve the productivity and also to have the minimum diameter wire for lowering the recast layer thickness, minimum hardness alteration and shorter manufacturing time.[14] Priyaranjan Sharma et al. conducted experiments on WEDM for Inconel 706 to evaluate *MRR* and *SR*. It was observed that thick recast layer was created due to the pulse-on time and high servo voltage. It was also observed that the microhardness value changed

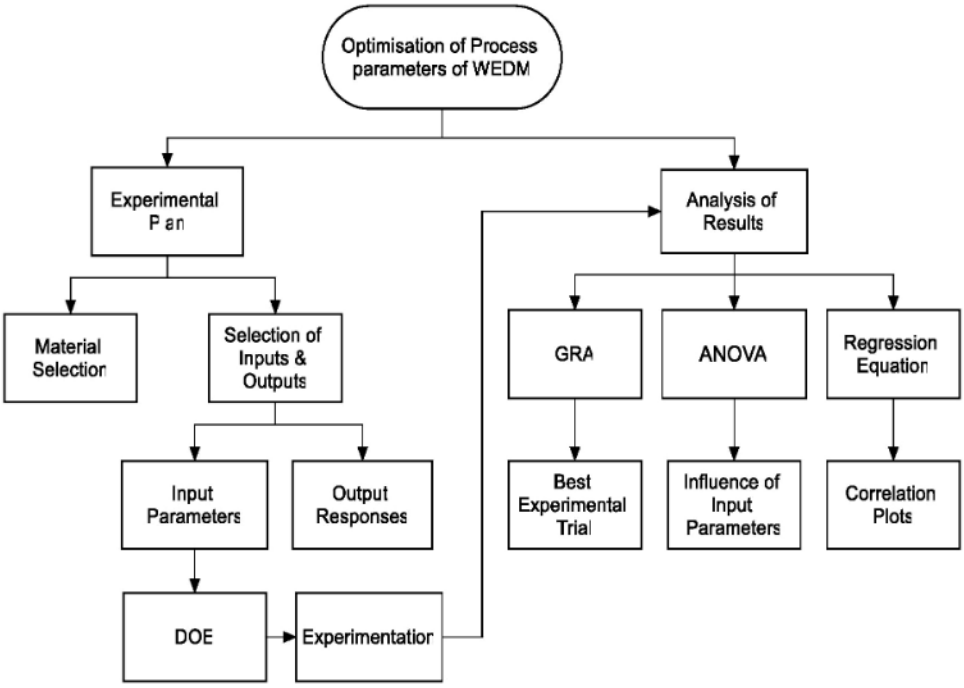

Figure 1: Flow diagram

in the sub-surface due to thermal degradation.[15] For obtaining the optimal combination of input combinations during the machining processes, various multi-objective optimization tools have been used by various researchers.[16,17,21,22]

From the literature survey, it is understood that most of the researchers have given due importance for the qualities of machined components, in particular *MRR* and *SR*. The non-traditional machining processes with different combinations of materials were considered by researchers in the past. The optimization of the machining process parameters with respect to various output responses had been attempted earlier. It was noticed that the optimization of the results was carried out for single and multiple criteria. Some of the researchers had chosen WEDM as one of the non-traditional machining processes for various materials and alloys. The present work is focusing on the optimization of the WEDM process parameters during the machining of an Inconel alloy 825 with an analysis of results using grey relational analysis (GRA). This combination of machining process and material combination with GRA had not been noticed in earlier literature, to the best of our knowledge.

2 PROPOSED RESEARCH

In the present work, taper profile machining of Inconel alloy 825 using a WEDM process has been chosen and experiments performed by varying the input parameters. The output responses of the *MRR*, *SR* and taper error (TE) have been considered. Design of experiments (DOE) has been employed to reduce the experimental trials. The number of experiments has been planned based on the L_9 Taguchi orthogonal array. The analysis of experimental results has been performed using Taguchi-based grey relational analysis (GRA). The most influencing process parameter has been identified using analysis of variance (ANOVA). The experimental results were used to generate regression equations to predict the output responses corresponding to any defined set of possible input parameters within the range. The correlation plots have been prepared to show the closeness of the regression results with the experimental results. The objectives and methodology of the proposed study are described in the next following section.

2.1 Objectives and methodologies

The objectives of the proposed study are presented below.

- Selection of material, experimental plan for WEDM process, selection of input process parameters and output responses for performing experimentation
- Grey relational analysis of the experimental results to identify the best experimental set based on ranking.
- ANOVA analysis of experimental results to predict the influence of process parameters on output responses.
- Modelling of regression equations to predict the output responses for a new set of input parameters.

The above objectives were achieved following the methodology described below in **Figure 1**.

The basics of WEDM, Taper profile machining, experimental plan, experimental results, grey rrelational analysis, ANOVA analysis, formation of the regression equation, and correlation plots are briefly described in the following sections.

3 WIRE ELECTRICAL DISCHARGE MACHINING (WEDM)

The wire electrical discharge machining (WEDM) process is an unconventional machining process in which the metal is removed from the parent metal using an electric spark created when the de-ionized water (dielectric) surrounds the machining zone. The basic metal removal is an electrothermal process. As the spark created between the gap of material and wire (electrode), the metal is locally melted and removed from the workpiece. The above process is suitable for producing complex shapes with high precision.

The WEDM machining is suitable for hard-to-machine material with sufficient accuracy, and the material should be conductive. A dielectric fluid is used to stop the sparking process from shorting. A significant advantage of the WEDM process is that it can remove the material without the application of a cutting force, thus producing a stress-free surface. The WEDM process causes significantly less damage to the workpiece and is suitable for machining hard materials. Therefore, the secondary and post-machining and thermal treatments are not required for the machined components. Further, the machined components will have significantly less thermal stress, and there is no chance for thermal distortion. The WEDM process is preferable for complex geometries and to create tiny and intricate shapes. As the process is not establishing direct contact between the tool and the workpiece, the machined surface will have a good surface finish, accurate and burr-free. Because of the advantages mentioned above, the WEDM process is commonly employed for mould and die manufacturing, automotive, aerospace and electronics industries. In WEDM, the wire is drawn from the spool in which it is wound. During the machining process, as the wire is in motion, only a small portion of the wire is used for producing the spark. The movement of wire is to be numerically controlled to get the complex three-dimensional shape. It is necessary to keep the wire in its position against the workpiece.

The significant advantages of the WEDM processes are listed below:

- WEDM is used to machine hard materials and alloys with higher thickness without forgoing the surface finish of the components.
- As WEDM process can produce a good surface finish and closer tolerance, the post-processing and surface treatments are avoided.
- The WEDM process is controlled by computer numerical control, and hence it is associated with accuracy and repeatability.

In the present work, the experiments have been performed using the WEDM machine EXCETEK V-650. The machine has five axes, and all the axes of the machine are servo-controlled and programmed with CNC codes, which are fed using a control panel. Each axis has an accuracy of 1 μm.The copper wire of diameter 0.25 mm and deionized water have been used for machining. The machine is capable of cutting a taper angle of 30°/100 mm.

3.1 Taper profile machining (TPM)

The manufacturing of components with angular surfaces often occurs during the machining of tools and dies of hard material. The process of such operations is termed as Taper profile machining (TPM). The TPM in the WEDM process is conveniently employed by offsetting the wire guides, appropriately based on the angle of the required surface. In the case of vertical machining, the upper and lower guides of the wires are aligned in line and for the taper cutting the guides are offset based on the angle required for machining. But in the case of taper cutting the wire tension fluctuates with a wide range and the deformation of the wire is observed if the taper angle is more. The taper angle set with the machine could not be produced precisely over the components for various reasons, such as wire deformation due to stiffness of the wire. If the angle set with the machine is termed as 'θ' and the angle produced over the components as 'Φ' then the taper error will be the difference between 'θ' and 'Φ'. It may be either positive or negative.

The TE in the taper cutting operation influences an adverse effect on the surface finish and geometrical accuracy of the workpiece. It is essential to minimize the TE occurring due to the wire deformation through the proper selection of a combination of process parameters to improve the surface integrity and machining performance.

4 EXPERIMENTAL PLAN

To optimize the process parameters, the profile machining has been performed using the WEDM process over Inconel 825 material by varying the process parameters. The output responses such as *MRR*, *SR* and TE have been predicted. The selection of material, input parameters, output responses have been described below.

4.1 Material selection

The Inconel 825 material is highly resistant to corrosion as well as phosphoric and sulfuric acids. It maintains its mechanical properties at higher temperatures, and the material is difficult to machine using a conventional machining process. It is an alloy material that contains nickel (39.64 %), iron (31.1 %) and chromium (2 %) as the major constituents. The chemical composition has been analysed using Optical Emission Spectrograph (OES). It is performed using the equipment OES-Foundry MASTER-PRO, OXFORD, Germany at the OMEGA Analytical Testing Laboratory located in Chennai.

4.2 Input parameters

The input machining parameters of the WEDM process such as pulse-on time (T_{on}), pulse-off time (T_{off}), wire tension (*WT*) and process parameter of taper angle (*TA*) have been considered for optimization. The input parameters have been considered in three levels within the available range and are presented in **Table 1**.

Table 1: Input parameters and their levels for machining

S. No.	Input factors	Units	Selected levels		
			I	II	III
1	Pulse-off time (T_{off})	μs	36	38	40
2	Pulse-on time (T_{on})	μs	0.6	0.7	0.8
3	Wire tension (*WT*)	N	12	13	14
4	Taper angle (*TA*)	°	1	3	5

The number of experiments to be performed and the set of input parameters for each experiment have been determined using design of experiments based on Taguchi's L_9 orthogonal array.

4.3 Output responses

Output responses considered for the study are the surface roughness (*SR*), material removal rate (*MRR*) and taper error (*TE*) for WEDM. The objective is to minimize the SR, TE and maximize the *MRR*. The method used for determining the above input parameters are described below.

Material removal rate (*MRR*): The weight of the metal removed is determined by subtracting the final weight of the workpiece from the initial weight of the workpiece in a specified time. For predicting the weight difference in the workpiece before and after the machining process, a Metis electronic weighing scale was used (capacity 30 kg), and the least count was noted to be 2 g. The *MRR* is determined using the following expression given in Equation (1):

$$MRR = \frac{\text{Material removed from the specimen}}{\text{Density}\times\text{Time taken}}\ \text{mm}^3/\text{min} \tag{1}$$

Surface Roughness (*SR*): *SR* is the irregularities present over the machined surface in the form of waviness due to the machining process. The *SR* is developed due to vibrations, work deflection, chatter and strains during machining. It is difficult to predict the location of the waviness over the surfaces and is not uniformly distributed. Hence, *SR* is qualitative but not quantitative. The *SR* is produced due to the method of manufacturing process rather than the machine.

SR is measured in terms of the average deviation from the nominal surface. It is measured as a square root of the arithmetic mean values of deviations from the mean line and it is denoted as '*Ra*'. The *SR* of the machined surfaces is measured using a Mitutoyo surface roughness tester.

Determination of taper error (*TE*): Taper error is the difference between the angle set with the machine and the angle produced over the machined samples. It is measured using the profile projector by projecting the magnified profile (outline) of the machined sample. The *TE* is computed from the measured angle and the angle initially set with the machine.

5 EXPERIMENTAL RESULTS

The test specimens, as illustrated below, have been cut by setting the taper profile. For the experimental analysis, a (100×100×15) mm Inconel 825 plate has been chosen. By using the WEDM process, the selected plate has been machined with a top face of 5 mm and a total thickness of 15 mm. The specimens were cut with 1°, 3° and 5° taper angles to the top face according to the experimental plan. Further, the machined surfaces have been measured for the output responses such as *MRR*, *SR* and *TE*. The nine experimental trials with their input parameters and corresponding output responses have been presented in **Table 2**.

Table 2: Experimental results

Exp. No.	Input parameters				Output responses		
	T_{off} (μs)	T_{on} (μs)	*WT* (N)	*TA* (°)	*MRR* (mm^3/min)	*SR* (μm)	*TE* (°)
EX01	36	0.6	12	1	13.3361	1.3	0.282
EX02	36	0.7	13	3	12.7791	3.01	0.272
EX03	36	0.8	14	5	12.2229	2.98	0.289
EX04	38	0.6	13	5	16.682	3.24	0.756
EX05	38	0.7	14	1	16.0223	3.05	0.143
EX06	38	0.8	12	3	15.5432	3.74	0.234

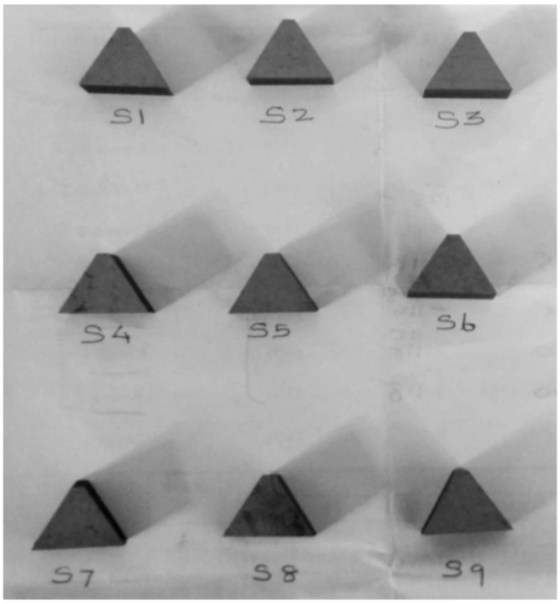

Figure 2: Machined specimens as per the experimental plan

EX07	40	0.6	14	3	19.8935	3.49	0.098
EX08	40	0.7	12	5	19.4503	2.45	0.068
EX09	40	0.8	13	1	18.8144	2.9	0.034

The machined specimens are presented in **Figure 2**. The best experimental trial is chosen among the above experiments is carried out using GRA. The procedures adopted for optimization is briefly described in the following sections.

6 GREY RELATIONAL ANALYSIS (GRA)

In real-world problems, the situation with no information and complete information are termed as black and white, respectively. When partial information is known, the situation is termed as grey. In the black situation, no solution is possible because of no information, whereas in white condition, a perfect unique solution is possible as complete information is available. In the middle, the grey region yields a variety of solutions from available solutions. It does not try to find the best solution instead it used the technique to determine a reasonably good solution for the chosen problem.

In the area of machining parameter optimization, the input parameters have been discretized into different levels and experimentation is planned based on DOE. The method suggests a few sets of input parameters to perform the experimentation instead of performing all the possible experiments. Then the output responses are predicted for a few sets of experiments and using an appropriate mathematical tool, the output responses are predicted for new sets of the input parameters.

In the present research, the nine sets of experimentation have been performed by varying the input parameters based on DOE. The output responses such as: *MRR*, SR and *TE* have been determined. The results are analysed using GRA. The influence of the input parameters with respect to output responses have been predicted using ANOVA tool.

GRA is an important part of the grey system theory pioneered by Professor Deng in 1982. A grey system means that a system in which part of the information is known and part of the information is unknown. In GRA, the degree of approximation among sequences is measured according to the Grey relational grade. In GRA, three distinct stages are present, such as normalization of data, evaluation of grey relational coefficient (GRC) and evaluation of grey relational grade (GRA) and briefly described below.

Step 1: The output responses such as *MRR*, *SR* and *TE* values of experiments are in different units, and hence all the values are required to be normalized before applying GRA. After normalization, the values of the data will be converted and lie between 0 and 1. This process converts the original data into comparable data. Based on the nature of the data obtained, a criterion such as "smaller is the better" or "larger is the better" will be used. In the present case, the *MRR* is to be maximized, and hence the "Larger is the Better" (LB) criterion is used. On the other hand, the SR and TE are to be minimized and hence the "Smaller is the Better" (SB) criterion is employed. The equations used for the normalization of the experimental data corresponding to LB or SB are given in Equations (2) and (3), respectively.

Larger is the Better (LB),

$$X_i(k)=\frac{x_i^0(k)-\min(x_i^0(k))}{\max(x_i^0(k))-\min(x_i^0(k))} \qquad (2)$$

Smaller is the Better (SB),

$$X_i(k)=\frac{\max(x_i^0(k))-x_i^0(k)}{\max(x_i^0(k))-\min(x_i^0(k))} \qquad (3)$$

where:

k – number of output responses and it varies from 1, 2, 3, …, n,
i – number of input trails it ranges from 1, 2, 3, … m,
$X_i(k)$ – normalized value of the variable 'k', and
$X_i^0(k)$ – values corresponding to the original sequence,
max($x_i^0(k)$) – largest value of the original sequence, and
min($x_i^0(k)$) – smallest value of the original sequence.

Step 2: The GRC is calculated for the output responses using the normalized values and its deviation sequence (Δ_{oi}) which is given by Equations (4) and (5) for the LB and SB criterion, respectively.

$$\Delta_{oi}=1-\left|x_i^0(k)-\min(x_i^0(k))\right| \text{ for LB criterion} \qquad (4)$$

$$\Delta_{oi}=\left|\max(x_i^0(k))-x_i^0(k)\right| \text{ for SB criterion} \qquad (5)$$

The GRC is computed using the above deviation using the following Equation (6).

$$\xi(k)=\frac{\Delta_{\min}+\xi\Delta_{\max}}{\Delta_{oi}(k)+\xi\Delta_{\max}} \qquad (6)$$

$\Delta_{\min}$ and $\Delta_{\max}$ are the minimum and maximum values of the absolute difference 'Δ_{oi}' of all the comparing sequence. 'ξ' is the identification coefficient, and the range is between 0 and 1. In general, it is considered as 0.5.

Step 3: The GRG corresponding to all the output responses are determined from the results of the above steps using the equation shown below in Equation (7):

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi(k) \qquad (7)$$

γ_i – required GRG for the i^{th} experiment for a number of responses, n.

It represents the coordination level of the reference sequence and comparability sequence. It also represents the overall quality characteristics. This process converts the multiple responses to a single response and compares them to select the best response using Taguchi's approach and thereby, the corresponding parameters can be chosen as the best one. The GRG of multiple responses are combined and converted into a single response by taking average values, and they are ranked. The corresponding experiment with a better performance characteristic is ranked first. GRG are ranked based on their values.

The optimal experimental set of process parameter combinations is predicted using GRA. Further, for determining the parameter, which significantly affect the output responses are predicted using a mean effect plot (MEP) for the output responses with the aid of Minitab Software.

Normalization of the data: The maximum and minimum values of *MRR* among the trails R01 to R09 are identified as max($x_i^0(k)$), min($x_i^0(k)$) from **Table 5** and the values are identified as 19.8935 mm³/min and 12.2229 mm³/min, respectively. The normalized value of *MRR* (NMRR) corresponding to the 1st trial is arrived at using Equation (2) and presented in Equation (8):

$$NMRR=\frac{(13.3361-12.2229)}{(19.8935-12.2229)}00.1451 \tag{8}$$

The experimental values of SR presented in **Table 4** are normalized by employing the criterion SB as per the Equation (3). The maximum and minimum values, max($x_i^0(k)$), min($x_i^0(k)$), corresponding to this series from R01 to R09 are identified as 3.74 μm and 1.3 μm. The experimental value of SR corresponding to R01 is normalized using Equation (3) and presented in Equation (9):

$$NSR=\frac{(3.74-1.3)}{(3.73-1.3)}=1 \tag{9}$$

In a similar way, the normalized value of the taper error (NTE) for the first experimental run is calculated corresponding to the smaller the better criterion using the Equation (3) and presented in Equation (10):

$$NTE=\frac{(0.756-0.282)}{(0.756-0.034)}=0.6565 \tag{10}$$

Finding the Grey Relational Coefficient (GRC): The GRC corresponding to each experimental value of *MRR*, *SR* and *TE* are derived from the normalized value of each series. Before determining the GRC, the deviation of the output responses 'Δ_{oi}' is derived as per the Equation (3) and (4) based on the output response to be maximized or minimized using the criteria LB or SB.[16–18]

The deviation of the experimental value uses the maximum and minimum values of the series and it is '1' and '0', respectively, as the values are normalized. The 'Δ_{oi}' value corresponding to the *NMRR*, *NSR* and *NTE* of R01 trail is calculated and presented in Equations (11), (12) and (13), respectively.

$$\Delta_{oi}\text{ for }NMRR=1-(0.145-0)=0.855\text{ (LB criterion)} \tag{11}$$

$$\Delta_{oi}\text{ for }NSR=(1-1)=0\text{ (SB criterion)} \tag{12}$$

$$\Delta_{oi}\text{ for }NTE=(1-0.657)=0.343\text{ (LB criterion)} \tag{13}$$

The identification coefficient 'ξ' is taken as 0.5. The minimum and maximum of the deviation series values for the *NMRR*, *NSR* and *NTE* series, are '1' and '0', respectively. Further, the GRC is calculated for *MRR*, *SR* and *TE* is performed using Equation (5) and presented in Equations (14), (15) and (16):

$$GRC\text{ for }MRR=\frac{0+(0.5\times1)}{0.855+(0.5\times1)}=0.369 \tag{14}$$

$$GRC\text{ for }SR=\frac{0+(0.5\times1)}{0+(0.5\times1)}=1 \tag{15}$$

$$GRC\text{ for }SR=\frac{0+(0.5\times1)}{0.343+(0.5\times1)}=0.593 \tag{16}$$

The calculated values of the normalized value, deviation sequence value and GRC from the experimental output responses corresponding to each response such as *MRR*, *SR* and *TE* have been presented in **Table 3a**.

Finding the Grey Relational Grade (GRG)

The GRG for each output response (γ_i) is determined using Equation (7). In the case of the multi-criterion environment, the GRC of all the '*n*' parameters are summed to get a single GRG for an experimental trial the average of the total GRC is determined. The GRG for trial 01 is computed and presented in Equation (17).[19–21] The average value is determined for the trial 01 is arrived at by dividing the value by the number of output responses and

Table 3a: GRC value generation for *MRR*, *SR* and *TE*

Output response	EX01	EX02	EX03	EX04	EX05	EX06	EX07	EX08	EX09	
MRR	Exp	13.336	12.779	12.223	16.682	16.022	15.543	19.894	19.450	18.814
	Nor	0.145	0.073	0.000	0.581	0.495	0.433	1.000	0.942	0.859
	Devi	0.855	0.927	1.000	0.419	0.505	0.567	0.000	0.058	0.141
	GRC	**0.369**	**0.350**	**0.333**	**0.544**	**0.498**	**0.469**	**1.000**	**0.896**	**0.780**
SR	Exp	1.300	3.010	2.980	3.240	3.050	3.740	3.490	2.450	2.900
	Nor	1.000	0.299	0.311	0.205	0.283	0.000	0.102	0.529	0.344
	Devi	0.000	0.701	0.689	0.795	0.717	1.000	0.898	0.471	0.656
	GRC	**1.000**	**0.416**	**0.421**	**0.386**	**0.411**	**0.333**	**0.358**	**0.515**	**0.433**
TE	Exp	0.282	0.272	0.289	0.756	0.143	0.234	0.098	0.068	0.034
	Nor	0.657	0.670	0.647	0.000	0.849	0.723	0.911	0.953	1.000
	Devi	0.343	0.330	0.353	1.000	0.151	0.277	0.089	0.047	0.000
	GRC	**0.593**	**0.603**	**0.586**	**0.333**	**0.768**	**0.643**	**0.849**	**0.914**	**1.000**

presented in Equation (17). In the present case, three responses have been considered.

For the first experimental run,

$$g_i = \frac{1}{3}\left[GRG_{\mathrm{MRR}} + GRG_{\mathrm{SR}} + GRG_{\mathrm{TE}}\right] = \frac{1}{3}\left[0.369 + 1.000 + 0.593\right] = 0.654 \tag{17}$$

The GRG values predicted for all the experimental trials are ranked, and the top-most ranked trial is considered to be the best among the available trails in terms of considered output responses. The *MRR*, *SR* and *TE* output responses, their GRC, GRG and its ranking corresponding to various trials have been presented in **Table 3b**.

Table 3b: GRC, GRG values and ranking of the experimental runs

Exp. No	*GRC*			*GRG*	*Rank*
	MRR	*SR*	*TE*		
EX01	0.369	1.000	0.593	0.654	4
EX02	0.350	0.416	0.603	0.456	7
EX03	0.333	0.421	0.586	0.447	8
EX04	0.544	0.386	0.333	0.421	9
EX05	0.498	0.411	0.768	0.559	5
EX06	0.469	0.333	0.643	0.482	6
EX07	1.000	0.358	0.849	0.736	3
EX08	0.896	0.515	0.914	0.775	1
EX09	0.780	0.433	1.000	0.738	2

In the present case, the EX08 reaches the first rank, and it is considered to be the best among all the trials that maximise *MRR* and minimize *SR* and *TE*. It is corresponding to the input parameters of 40-μs pulse-off time, 0.7-μs pulse-on time, 12-N wire tension and 5-degree taper angle. The obtained GRG values have been analysed using Minitab software version 14.0 with the consideration of *S/N* ratio values. *S/N* ratio refers to the variation in the output results due to the influence of noise factors (uncontrollable factors) during the machining process. This has been included in the revised manuscript. The main effect plot (MEP) for the *S/N* ratio values of the GRGrade values is presented in **Figure 3**.

The results of the main effect plots confirmed that the input combination (A3 – B1 – C1 – D1) would yield a better result for the considered output responses. Hence, the results for the combination (A3 – B1 – C1 – D1) need to be evaluated.

7 ANALYSIS OF VARIANCE (ANOVA)

The analysis of the variance (ANOVA) is used to investigate which input parameters significantly affect the quality characteristic. By using the GRG value, ANOVA is attempted for identifying the significant factors. In addition to the degree of freedom (DF), the mean of squares (MS), the sum of squares (SS), the *F*-ratio and the contribution (C) associated with each factor were also found. The factor significantly affecting the performance characteristics was the one that has more contribution.

ANOVA is performed with the aid of Minitab software version 14.0 to reveal the percentage influence of

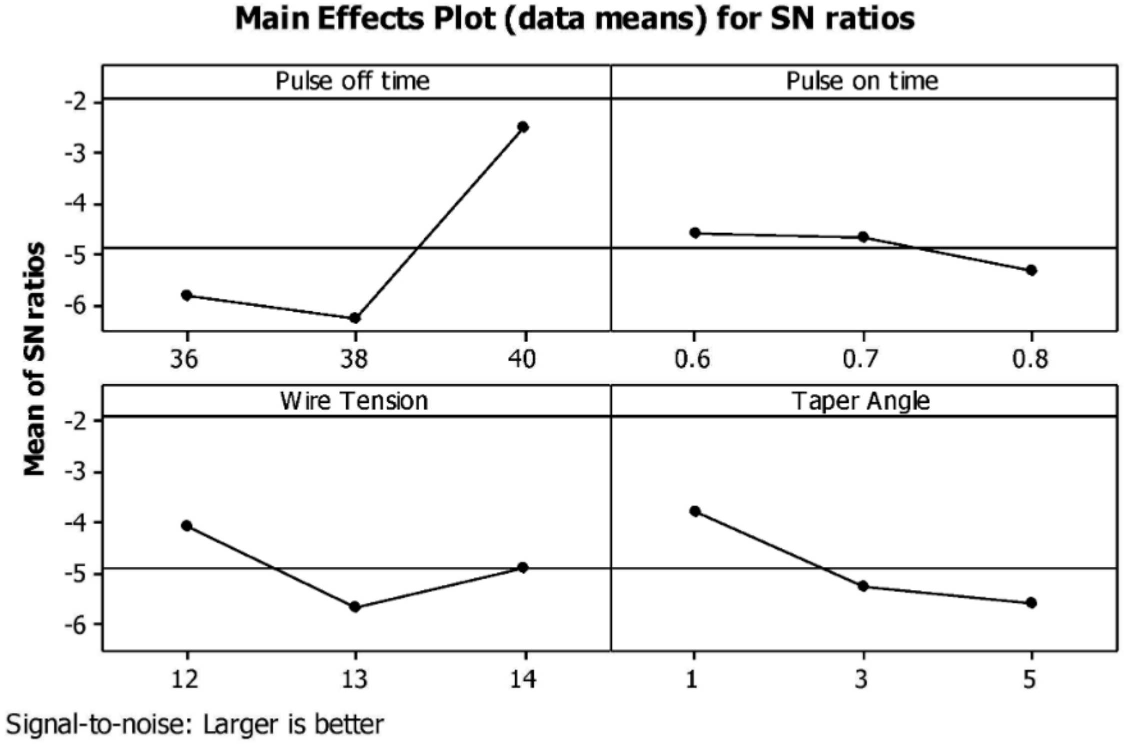

Figure 3: Main effect plot of *S/N* ratio values of *GRG*

Table 4: ANOVA results for the machining process parameters of WEDM

Control factors	Symbol	Degree of freedom (DF)	Sum of squares (SS)	Mean of squares (MS)	Contribution *C* (%)
Pulse off time (μs)	A	2	0.123029	0.061514	76.45
Pulse on time (μs)	B	2	0.004034	0.002017	2.51
Wire tension (g)	C	2	0.014701	0.007350	9.13
Taper angle (°)	D	2	0.019173	0.009586	11.91
Total		8	0.160937	0.080467	100.00

Table 5: Comparison of output responses of experimental and regression equations

Trial No.	Input parameters				*MRR* (mm^3/min)		SR (μm)		TE (Deg.)	
	T_{off} (μs)	T_{on} (μs)	*WT* (kgf)	*TA* (°)	Exp.	Reg.	Exp.	Reg.	Exp.	Reg.
EX01	36	0.6	12	1	13.3361	13.3361	1.3	1.30008	0.282	0.28333
EX02	36	0.7	13	3	12.7791	12.7791	3.01	3.01007	0.272	0.27344
EX03	36	0.8	14	5	12.2229	12.2229	2.98	2.98006	0.289	0.29055
EX04	38	0.6	13	5	16.682	16.682	3.24	3.24007	0.756	0.75752
EX05	38	0.7	14	1	16.0223	16.0223	3.05	3.05008	0.143	0.14463
EX06	38	0.8	12	3	15.5432	15.5432	3.74	3.74008	0.234	0.23537
EX07	40	0.6	14	3	19.8935	19.8935	3.49	3.49008	0.098	0.09972
EX08	40	0.7	12	5	19.4503	19.4503	2.45	2.45008	0.068	0.06944
EX09	40	0.8	13	1	18.8144	18.8144	2.9	2.90009	0.034	0.03556

each input factor on achieving the optimal results for all the output responses. The ANOVA table is presented in **Table 4** with the complete details.

The ANOVA results for the considered WEDM process parameters have been presented above without considering the error values. The results of the ANOVA reveal that the percentage contribution of pulse-off time (μs), pulse-on time (μs), wire tension (g) and taper angle (degree) influencing the multiple performance characteristics were 76.45 %, 2.51 %, 9.13 % and 11.91 %, respectively. From the percentage contribution of the ANOVA, it is estimated that the pulse-off time was the parameter most significantly influencing the Grey relational grade. And the pulse-on time was the factor having least effect on the performance.

8 REGRESSION EQUATIONS GENERATION

The outcome of the experiments corresponding to the set of input parameters is used to generate regression equations using design expert software version 7.0.0 for each output response. Thus formed regression equations are capable of predicting the output response for any possible set of input parameters within the specified range. However, it is required to check the capability of predicting the output responses by the generated regression equations. Its capability is justified by plotting the correlation plots between the results of the experimental and regression equations for the same set of input parameters. The generated regression equations corresponding to the output responses of *MRR*, *SR* and *TE* are presented below as (18, 19 and 20), respectively.

$$MRR = -39.83595 + (1.57946{*}A) - (10.86033{*}B) + (0.050733{*}C) + (0.021150{*}D) + (0.13783{*}A{*}B) - (0.00188333{*}A{*}C) + (0.004{*}B{*}C) + (0.00000416667{*}A^2) \quad (18)$$

$$SR = -53.73833 + (1.22167{*}A) - (35.1{*}B) + (2.65333{*}C) + (0.27833{*}D) + (2.15{*}A{*}B) - (0.105{*}A{*}C) + (8.7{*}B{*}C) + (0.055{*}A^2) \quad (19)$$

$$TE = 29.28925 + (1.19738{*}A) - (65.475{*}B) - (4.5395{*}C) + (0.19925{*}D) + (1.68333{*}A{*}B) - (0.12117{*}A{*}C) + (0.135{*}B{*}C) + (0.052646{*}A^2) \quad (20)$$

The various input parameters used in the above equations are A – pulse-off time; B – pulse-on time; C – wire tension; D – taper angle. The effectiveness of the regression equation has been established by predicting the output responses corresponding to the set of input parameters using the above equations. The outcomes of the output responses of experiments and regression equations corresponding set of input parameters have been determined and presented in **Table 5**.

To illustrate the correlation among the experimental and regression outcomes, the results presented in **Table 5** corresponding to *MRR*, *SR* and *TE* have been plotted and shown in **Figures 4a** to **4c**, respectively.

The closeness of each output response of *MRR*, *SR* and *TE* in the above equations are denoted by its regression coefficient values. In the above equations, the regression coefficients for *MRR*, *SR* and *TE* are obtained as *R*-squared valued from the design expert software are 1, 1, and 1, respectively.

From the regression results, it can be concluded that the regression equation of *SR* and *MRR* can be comfortably employed for predicting the output responses of any set of input parameters within the specified range. It is to be noticed that the above validation is not commonly employed for all machines. It is liable to vary from ma-

Table 6: Prediction of output responses using the generated regression equations

S. No.	Randomly chosen input combinations				Predicted output responses		
	T_{off} (μs)	T_{on} (μs)	*WT* (N)	*TA* (°)	*MRR* in (mm^3/min)	*SR* in (μm)	*TE* in (°)
1.	36	0.6	12	3	13.37839	1.85674	0.68183
2.	36	0.7	13	5	12.82138	3.56673	0.67194
3.	38	0.6	13	3	16.63969	2.68341	0.35902
4.	38	0.7	13	5	16.12491	3.61007	0.78217
5.	40	0.7	14	1	19.32207	2.86342	0.07604

chine to machine based on its capability. For five input combinations which were not in the experimental plan, the output responses have been predicted using the generated regression equations and presented in **Table 6**. By comparing the results with that of the optimal input combination, it was found that the results of all those combinations were not better than them.

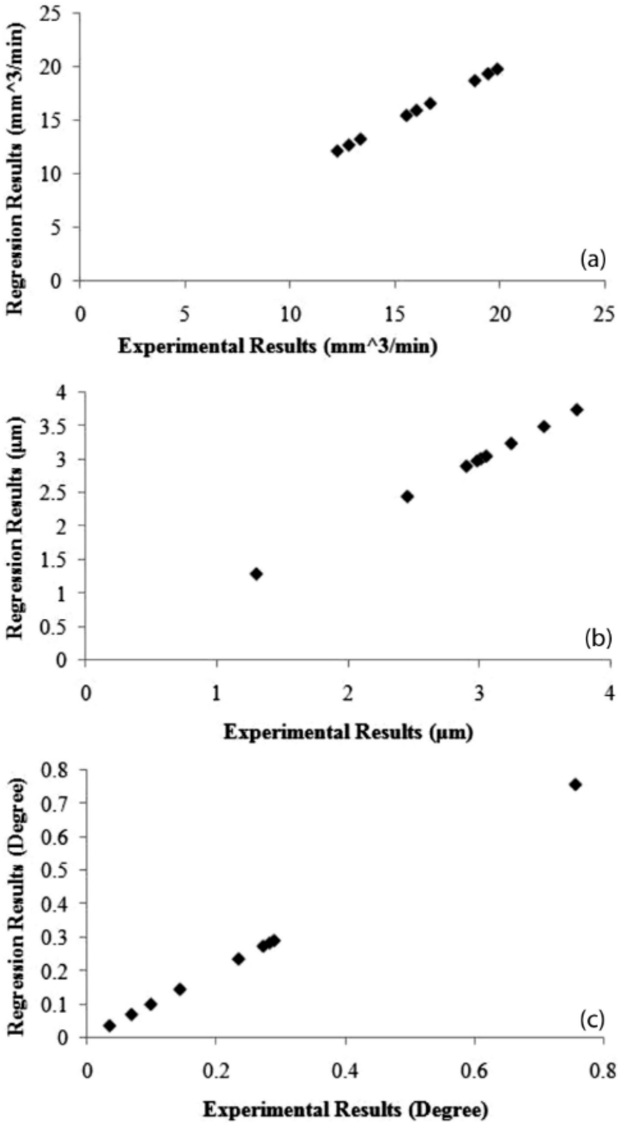

Figure 4: a) Correlation plot for *MRR*, b) correlation plot for *SR*, c) correlation plot for *TE*

9 CONCLUSIONS

The machining process parameter optimization of a WEDM process with Inconel alloy 825 has been considered in the current study. The tapered profile has been machined with taper error as one of the output responses. The input parameters have been considered at three different levels, and the number of experiments to be performed has been decided based on the L_9 orthogonal array. The output responses. *MRR*, *SR* and *TE* have been considered. The experimental results were analysed using GRA, and the best experimental trial that optimizes all the output parameters simultaneously has been predicted. The results of the Taguchi-based Grey relational analysis revealed that 40-μs pulse-off time, 0.6-μs pulse-on time, 12-N wire tension and 1-degree taper angle yielded the most desirable output values, which are 19.896 mm^3/min: *MRR*, 0.333 μm *SR* and *TE*: 0.0754° TE. The influence of the input parameters over the output responses has been analysed using ANOVA. From the ANOVA results, it was identified that pulse-off time was the most influencial process parameter for achieving the optimal output responses. The prediction of the output response for an unknown set of input parameters within the specified range has been performed by generating regression equations for individual outputs. The correlation plots between the experimental and regression equation results have been plotted to identify the fitness of the proposed equations. The process briefed is very well accommodated for any other non-traditional machining process for the optimization of its parameters. It is expected that the present article has thrown the light on the optimization of the process parameters for the researchers involved in the manufacturing area using non-traditional machining.

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