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A Research on Investigating the Optimization of Process Parameters of Aluminum Alloy 6061 by using Wire EDM

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Abstract: In this paper, the wire electric discharge machining (WEDM) of Aluminium alloy 6061 is studied. The prime objective is to optimize metal removal rate (MRR) and surface roughness (SR) using multi-response optimization. To obtain high quality during machining process, the selection of optimal cutting parameters is very important. The four process parameters viz. current (I_P), pulse on time (T_{on}), pulse off time (T_{off}) and servo voltage (SV) have been considered in this study for optimal settings, for machining of the material. Taguchi method and Grey relational analysis (GRA) technique have been used to obtain the optimal process parameters for the responses of interest. The L_{16}orthogonal array based on Taguchi method is used to find the optimum process parameters. ANOVA (analysis of variance) is used with Minitab16 to determine the process parameter which mainly effects MRR and SR. The pulse on time (T_{on}) is found to be the main factor effecting MRR and SR.
Keywords: ANOVA, Al alloy 6061, GRA, MRR, SR, Taguchi method, WEDM.

I. INTRODUCTION

Electric discharge machining (EDM) is defined as process of electro-thermal non-conventional machining type in which electrical energy is used to produce electrical sparks and material removed by the thermal energy of sparks. Electric discharge machining is mostly used to machine high temperature resistant alloys materials and is hard to-machine by conventional machining process. EDM can be utilized to machine complex geometries.

Work material to be machined by EDM must be electrically conductive .WEDM is a machining procedure in which an electrode that goes through a fixed path to cut conductive materials without considering their hardness and strength. It is able for delivering a fine, exact, corrosion resistant and wear resistant surfaces [1].

In Wire EDM, a constantly moving conductive material is worked as an electrode and material is removed from the work piece by a progression of discrete sparks between the work piece and wire electrode isolated by a thin film of dielectric liquid [2]. The dielectric fluid is constantly passed to the spark area to flush away the eroded material and it also works as a coolant. During the WEDM process, there is no immediate contact between the work piece and the wire.

WEDM uses a constantly travelling wire electrode made of thin brass, molybdenum, copper or tungsten of diameter 0.05-0.50 mm, which is fit for accomplishing less corner radii. Wire EDM has high potential in recent times in the metal cutting industry for accomplishing a high dimensional accuracy, surface machining and forming contour elements of items or parts. The troubles faced in the die sinking electric discharge machining are removed with Wire EDM as complicated design tool is removed by moving conductive wire and relative motion of wire guides.

Wire EDM method combines a thin wire as an electrode changes electrical energy to thermal for cutting of the materials. The schematic representation of WEDM cutting process is shown in Fig.1.

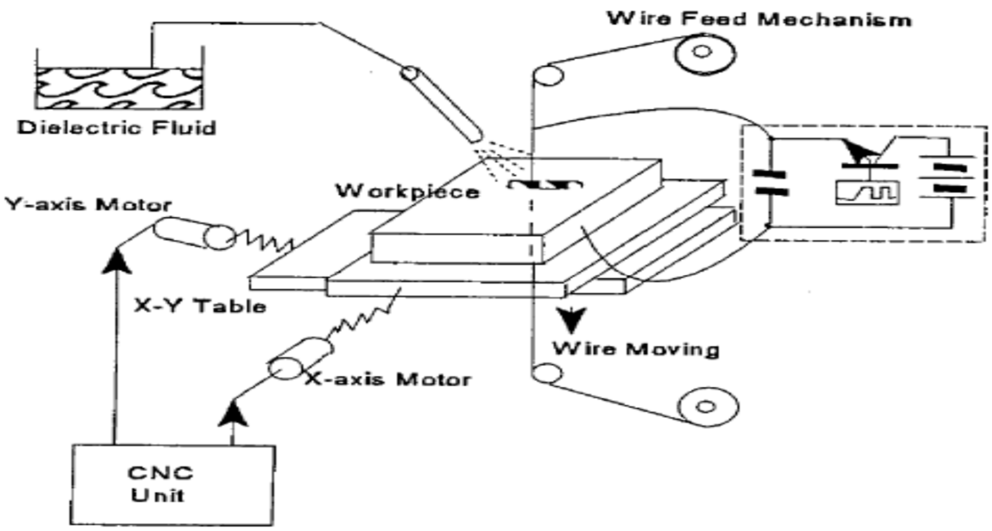

Fig.1: Wire EDM Process

II. LITERATURE REVIEW

Sharma et al. [2016] investigated machining parameters for cutting speed, die width and Surface roughness of H-21 die tool steel in WEDM. The L_{18} orthogonal array based on Taguchi method is used to find the optimum process parameters. The five process parameters viz. peak current, pulse on time, pulse off time, wire speed and wire tension have been considered in this study for optimal settings, for machining of the material. It concluded that average cutting speed is mostly affected by pulse on, pulse off, peak current and wire feed during ruff cut and there is no most significant factor that affects the surface roughness.

Kumar et al. [2016] studied the effects of machining parameters on the material removal rate of Stainless steel (SS 304) in WEDM. The three process parameters viz. pulse on time, pulse off time and servo voltage has been considered in this study for optimal settings, for machining of the material. The design of experiment is based on Taguchi Design approach L_9orthogonal array. The analysis of results indicated that diffused wire gives more material removal rate (MRR) as compare to the brass wire. The results showed that the pulse on time and servo voltage has the highest influence on material removal rate (MRR).

Kumar et al. [2016] reported an experimental study on rough cut, trim cut using distilled water as a dielectric fluid and Al & Si metal powders in dielectric fluid for WEDM of Nimonic-90. First, the influence of discharge energy (DE) in rough cut is evaluated for machining rate and surface roughness and compared with trim cut without any metal powder additives in dielectric fluid. The effect of Al and Si metal powders (varying concentration of 1g/L, 2g/L and 3g/L) in dielectric fluid is studied separately and comparison is also made for MR, SR, recast layer and micro hardness of machined Nimonic-90. From the results it is observed that using trim cut, a fine and uniform surface texture is obtained irrespective of the high discharge energy of rough cut. Al and Si powders additives show a significant reduction in MR for trim cutting operation whereas a remarkable modification is obtained in surface textures after trim cut using metals powder mixed dielectric. Panda et al. [2016]investigated and optimized the machining parameters viz. Pulse on time, Duty cycle & current for MRR of EDM of aluminium alloy 6061 by using copper electrode. The significant parameter for MRR is determined by using S/N ratio and ANOVA. The optimum parameters setting obtained as Pulse on time 100 µs, Duty cycle 10, Current 30 A. From AVOVA, it was concluded that among all the parameters Current has a significant effect on the response. Nataraj and Ramesh [2016] investigated WEDM of aluminium based metal matrix composite was fabricated successfully through stir casting technique. The following conclusions are derived from WEDM of Al 6061 metal matrix composite reinforced with 5%wt of Al O, 3% wt. of SiC and 2%wt of E-glass fiber are as follows. Both the metal removal rate and surface roughness strongly depends on the current and pulse on time for the machining. The pulse off time has less effect on it. The optimum parameter of combination setting is current 12.40 Amps, pulse on time 30µs and pulse off time 7µs for maximizing the metal removal rate and minimizing the surface roughness. Raj et al. [2015] studied application of combined Response surface method is to improve the multi-response characteristics of MRR and SR in the Wire-Cut EDM of Pure Titanium. The present study develops MRR models for three different parameters viz. wire tension, pulse on time and pulse off time for Wire EDM process for machining pure titanium using response surface method. It was found that all the three process parameters and some of their interactions have a significant effect on MRR. The MRR tends to increase, significantly with increase in pulse on time for decreases with pulse off time. Pramanik and Basak[2015] studied that the longer pulse on time generated more heat and facilitated the removal rate of material to any other materials, the increase of pulse on time increases the removal rate of material for 6061 Aluminium alloy. The surface roughness is found to decrease with the increase of wire tension. The longer pulse on time induces higher wear in the wire electrode. On the other hand, higher tension in the wire electrode reduces the wear by providing steady machining. Tapered slots were produced due to progressive wear of the wire electrode. The amount of taper increased with the increase of the electrode wear. ashid et al. [2014] studied the parametric optimization using Taguchi method for WEDM of steel grade EN 9 component. The three process parameters viz. Pulse on-time, Pulse off-time and wire feed. The experimentation is conducted by using Taguchi's L9 orthogonal array. The results are analyzed using analysis of variance (ANOVA) and response graphs and presented. Khan et al. [2014] studied that the effect of the WEDM parameters on the SR and the micro hardness of the High Strength Low Alloy steel (ASTM A572-grade 50). The L_9 orthogonal array based on Taguchi method was performed and GRA method is subsequently applied to determine an optimal WEDM parameter setting. The SI parameters i.e. surface roughness and micro hardness are selected as the quality targets. The pulse off-time is found to be the most influential factor for both the surface roughness and the micro-hardness. The results of ANOVA concluded that the pulse off-time is the most significantly controlled factor for affecting the SI in the WEDM. Li et al. [2014] studied on the evolution process of surface integrity and machining efficiency of WEDM of IN718 (Nickel-based Alloy) by one rough cut (RC) mode followed by three trim cut (TC) modes. Material removal efficiency, surface roughness, surface topography, surface alloying, and micro hardness have been characterized. Results show that high material removal efficiency can be achieved in WEDM. Six-sigma distribution of Ra in RC mode is different from that of TC modes. The high toughness of IN 718 would be the major contributing factor to the absence of micro cracks in the TC modes. Jindal et al. [2014] reported the effect of cutting parameters on Material Removal rate and Surface Roughness during turning of AISI H21 steel under dry machining condition using Response surface methodology (RSM). CNMG 120412 MP of Grade TT 8135 has been selected as cutting tool material AND experiments are done on HMT CNC lathe machine Stallion-100 HS. The experimental results indicated that MRR increases with the increase in feed rate, spindle speed and depth of cut. It is also seen that the Surface roughness decreases with increase in spindle speed but increases with increase in feed rate.

Sivanaga et al. [2014] studied the selection of best process parameter of WEDM while machining 18-4-1 grade speed steel (HSS) of different thickness from 5mm to 80mm. Experiments were done on work piece by varying power input and condition of best power value with stable machining and high cutting speed is recognized. Then all performance measures are evaluated like surface roughness, Material removal rate, Spark gap etc. Experiments were repeated with all different thickness of work piece material. Later on mathematical correlation was developed with software. Finally, this correlation and parameter evaluation are studied to choose best process parameter. Joshi et al. [2014] studied the control parameters required for machining of tool steel. EN 31 is used vastly in engineering applications. The objective of the research paper is to analyse the cutting speed and Metal removal rate of tool steel. The Metal removal rate can be controlled by machining parameters which can be controlled and set according to the hardness and cutting speed. The process parameters taken are pulse on time, pulse off time, bed speed and current. Machine used for experiment is Electronica DL-25P unit four axis CNC Wire-cut electrical discharge machining (WEDM).He concluded that, the better Parameter setting is Pulse on 24µs, pulse off 6 µs, Bed speed 35 µm/s. Sachdevaet al. [2013] studied of metal cutting focuses on the features of tools, input work materials and machine parameter settings influencing process efficiency and output quality characteristics by taking five WEDM process parameters are current, pulse on time, pulse off time, wire speed and wire tension. Experiments were carried out on H-21 die tool steel as work piece electrode and zinc coated brass wire as a tool electrode. Response parameters are cutting speed, surface roughness and die width. Taguchi's L_{18} orthogonal array technique along with S/N ratio and ANOVA has been used to evaluate optimal parameter combination to achieve optimal cutting speed, minimum surface roughness value and minimum die width; with selected experimental domain. Durairaj et al.[2013]studied the Grey relational theory and Taguchi optimization technique, in order to optimize the cutting parameters in Wire EDM for SS304. In this experiment Taguchi's L_{16}, orthogonal array has been used. The input parameters selected for optimization are gap voltage, wire feed, pulse on time, and pulse off time. For each experiment surface roughness and kerf width was determined by using contact type surf coder and video measuring system respectively. By using multi objective optimization technique grey relational theory, the optimal value is obtained for surface roughness and kerf width and by using Taguchi optimization technique, optimized value is obtained separately.

Muthuraman et al. [2012] performed experiments on (WC-CO) using different process parameters Pulse on time, Pulse off time, Ignition current, Wire feed and Dielectric pressure& to study their effect on surface roughness. DOE is used to study influence of Process variables on WEDM of Tungsten Carbide Cobalt Metal Matrix Composite. It was suggested that with increase in Pulse on time, Wire feed, then value of surface roughness increases but as increase in dielectric pressure takes place then surface roughness starts decreasing. Gupta et al. [2012]investigated the effect of parameters on kerf width for WEDM using HSLA as workpiece. It is revealed that kerf width decreases with increase in pulse on time, pulse off time, spark gap voltage and peak current. Kerf width increases with increase in wire tension. In order to evaluate the effect of selected process parameters, the response surface methodology (RSM) is used to formulate a mathematical model which correlates the independent process parameters with the desired kerf width. The analysis of results indicates that the spark gap voltage, pulse on time, peak current and pulse off time have a significant effect on kerf width. Gadakh et al. [2012] studied the application of TOPSIS (Technique of order preference similarity to ideal solution) is used for solving multi-criteria optimization problems in WEDM. Result obtained by this technique hold same as the result obtained by past researchers work. Input parameters were Gap voltage, Pulse on time, Pulse off time and Wire feed. Optimization of Multi performance characteristics like MRR, kerf was done using TOPSIS. The method represents selection of optimal process parameters in WEDM process using TOPSIS method. Kumar et al.[2011] investigated performance of WEDM parameter (SR) while machining Al6063/Sicp composite. Experiment suggested selection of 4 process parameters (Pulse on time, Pulse off time, gap voltage, wire feed). For this, Sic was mixed as 5%, 10% & 15% in different proportions in Aluminium using stir casting method and then machining of pure Al 6063 and Al MMC was done. It was observed that Surface Roughness (Ra) increases with increase in percentage fraction of Sic particles in MMC. Raoet al. [2010] investigated effect of input parameters in WEDM on MRR by using Aluminium BIS-24345 alloy as workpiece material. Different levels of input parameters were studied using Taguchi design L_{18} orthogonal array. The parameters viz. Pulse on time, Pulse off time, Peak current, flushing pressure of dielectric, wire feed rate, wire tension, spark voltage & servo feed were selected. First table was prepared using orthogonal array then ANOVA (analysis of variance) was done and lastly S/N ratio was used to calculate MRR. It was concluded that Peak current parameter was most significant, Pulse on time, Pulse off time, Spark voltage and Flushing pressure of dielectric are significant factor. While wire feed and wire tension is less significant parameter. Gill et al. [2010] investigated the effect of deep cryogenic treatment (DCT) on machinability of Ti 6246 alloy in electric discharge drilling (EDD) by conducting experimental investigations on the production of 10mm diameter blind holes with electrolytic copper tool. An attempt has also been made to compare the production accuracy of holes drilled in deep cryogenically treated Ti 6246 (DCT Ti 6246) alloy and no treated Ti 6246 alloy in terms of surface roughness and overcut. The result of study reveals the higher material removal rate (MRR) and wear ratio (WR), lower tool wear rate (TWR) in case of EDD of DCT Ti 6246 alloy work piece as compared with no treated Ti 6246 alloy work piece. Also superior production accuracy of holes is reported while EDD of DCT work piece. Lin, Wang, et al. [2009] studied machining performance of conductive ceramics (Al2O3 + 30vol% TiC) in WEDM. The WEDM machining parameters such as machining polarity, peak current, auxiliary current with high voltage, pulse duration, no load voltage, and servo reference voltage were chosen to explore the effects on material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR). The L18 orthogonal array based on the Taguchi experimental method was adopted to determine EDM machining characteristics systemically, and the experimental data were statistically analyzed by analysis of variance (ANOVA).

III. EXPERIMENTAL SET UP, DESIGN AND RESULTS

A. Experimental Set Up

The experiment work was performed in Sprintcut WEDM machine (Electronica Sprintcut WEDM) as shown in Fig. 2.The zinc coated brass wire electrode of diameter 0.25 mm was used for machining.

Fig.2.Experiment Setup of Sprint cut Wire EDM

B. Selection of Work Piece Material

In this work, Aluminium alloy 6061 is used. Aluminium alloy 6061 is alloy of precipitation-hardened type of the mostly used of the 6000 series Al alloys. It is an versatile heat treatable extruded alloy with medium to high strength capabilities. The Table1 shows typical Chemical composition of Al alloy 6061.

The aluminium alloy plate of rectangular type having size 200×100×10mmwas used for the experimental work. Before starting of experiment, one hole was drilled in the plate with wire EDM and seventeen square specimens of size 10×10 mm were cut. Al alloy6061 is normally used for the construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft commercial or military aircraft, ultra-high vacuum (UHV) chambers, parts of remote controlled model, helicopter rotor components [2].

Table1: Chemical Composition of Al alloy 6061

S. No	Component	Wt. %
1	Aluminium	Balance
2	Magnesium	0.8-0.12
3	Silicon	0.4-0.8
4	Iron	Max. 0.7
5	Copper	0.15-0.40
6	Zinc	Max. 0.25
7	Titanium	Max. 0.15
8	Manganese	Max. 0.1
9	Chromium	0.04-0.35
10	Others	0.05

C. Experiment Design

In this work four process parameters are used namely I_P, T_{ON}, T_{OFF}, SV have been considered in this study. The following parameters were constant during experiment namely with wire feed (8 m/min), wire tension (8 units),servo feed (2100 units) and flushing pressure (1 unit). These process parameters are done with four levels. TheTable2 show the different input parameters at four levels.

Table2:Input Variables Parameters and Their Levels

Sr. No.	Variables input	Unit	Level 1	Level 2	Level 3	Level 4
1	Peak Current(A)	Ampere	200	210	220	230
2	Pulse on time(B)	µs	120	122	124	126
3	Pulse off time(C)	µs	45	47	49	51
4	Servo voltage(D)	Volt	30	35	40	45

The selection of orthogonal array is concerned with the total degree of freedom of process parameters. The degree of freedom for the orthogonal array must be greater than or at least equal to given the process parameters. Thereby, L_{16} orthogonal array having degrees of freedom equal to 15 is considered in present case.

D. *Experiment Results*

Table 3: Experiment observations

Sr. No.	Peak Current(A)	Pulse on time(B)	Pulse off time(C)	Servo-voltage (D)	MRR Mean1	MRR SNRA1	SR Mean2	SR SNRA2
1	200	120	45	30	12.90	22.2118	3.58	-11.0777
2	200	122	47	35	13.30	22.4770	3.72	-11.4109
3	200	124	49	40	13.70	22.7344	3.88	-11.7766
4	200	126	51	45	14.07	22.9659	4.10	-12.2557
5	210	120	47	40	13.60	22.6708	3.85	-11.7092
6	210	122	45	45	13.80	22.7976	3.92	-11.8657
7	210	124	51	30	14.00	22.9226	4.07	-12.1919
8	210	126	49	35	14.81	23.4111	4.31	-12.6895
9	220	120	49	45	12.83	22.1645	3.54	-10.9801
10	220	122	51	40	13.63	22.6899	3.87	-11.7542
11	220	124	45	35	14.50	23.2274	4.20	-12.4650
12	220	126	47	30	15.50	23.8066	4.50	-13.0643
13	230	120	51	35	13.00	23.2789	3.62	-11.1742
14	230	122	49	30	13.80	22.7976	3.92	-11.8657
15	230	124	47	45	14.35	23.1370	4.18	-12.4235
16	230	126	45	40	16.00	24.0824	4.62	-13.2928

The above Table3 shows all experimental observations for MRR and SR. The experiments are done on above layout. After this the machining characteristics namely metal removal rate and surface roughness is measured.

$$Metal\ Removal\ Rate(MRR) = \frac{\text{Volume of material removed}}{\text{Cutting time}}$$

The MRR was measured in mm^3/min and surface roughness in µm.

E. *Optimization of Machining Characteristics*

In this work, Taguchi method is a power tool for parametric design of performance characteristics used to find out the optimum parameters. These optimum parameters are used to find out maximum cutting speed and metal removal rate and minimum surface roughness. The four control factors are used namely A, B, C, D. The obtained experimental observations are now converted into S/N ratios. The obtained S/N ratios obtained depend on various characteristics.

Based on the machining characteristic which has higher value represents better machining performance, such as cutting speed, is called ‘higher is better, HB’.

Inversely, the characteristic which lower value represented better machining performance, such as surface roughness, is called ‘lower is better, LB. Therefore, ‘HB’ for the cutting speed and ‘LB’ for the SR were selected for obtaining optimum machining performance characteristics. The loss function (L) for objective of HB and LB are stated as follows.

$$L_{HB} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2{}_{cs}}. \qquad ....(1.1)$$

$$L_{LB} = \frac{1}{n}\sum_{i=1}^{n} y^2{}_{sf}. \qquad ....(1.2)$$

Where y_{cs}, y_{sf} are response for cutting speed and surface finishing respectively and n denotes the number of experiments.

The S/N ratio may be calculated as a logarithmic transformation of the loss function as showed below.

S/N ratio for cutting speed = $-10 \log_{10} (L_{HB})$ …. (1.3)

S/N ratio for Surface Roughness = $-10 \log_{10} (L_{LB})$ … (1.4)

To find the effect of each level of process parameters on machining characteristic response table is used.
Taguchi method is used to find the response table. Firstly the mean values of machining characteristics belonging to each level are found. After that the averages are found and the process parameters which effect mainly MRR and SR are found.

F. Response Tables

1) Response Tables for MRR

Table4: Response Table for S/N Ratio (Higher is better)

Level	Peak Current(A)	Pulse on time (B)	Pulse off time(C)	Servo voltage (D)
1	22.60	22.33	23.08	22.93
2	22.95	22.69	23.00	22.05
3	22.98	23.01	22.80	23.04
4	23.10	23.57	22.70	22.77
Delta	0.48	1.24	0.37	0.28
Rank	2	1	3	4

Table 5: Response Table for Means (Higher is better)

Level	Peak Current	Pulse on time	Pulse off time	Servo voltage
1	13.49	13.08	14.30	14.05
2	14.05	13.63	14.19	13.90
3	14.12	14.14	13.79	14.13
4	14.29	15.10	13.68	13.76
Delta	0.79	2.01	0.63	0.47
Rank	2	1	3	4

The above Tables(4-5) represent responses of MRR for S/N ratio and means respectively.

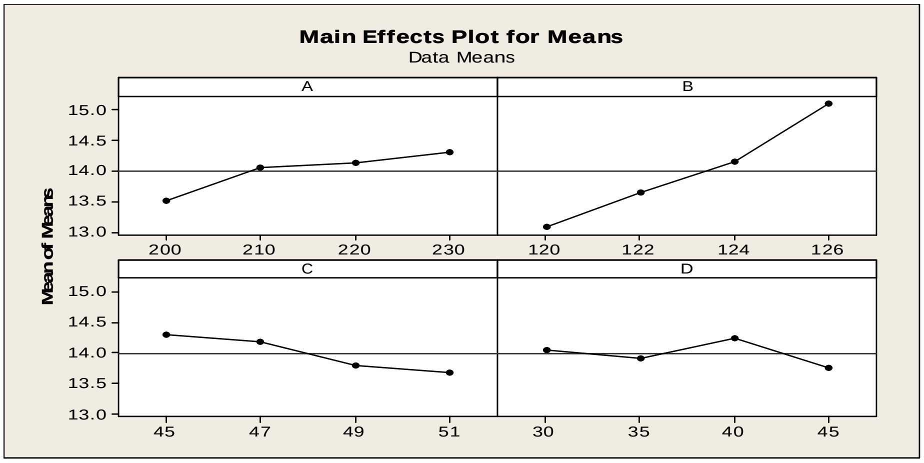

Fig.3. Main Effect Plot for Means (for Material Removal Rate)

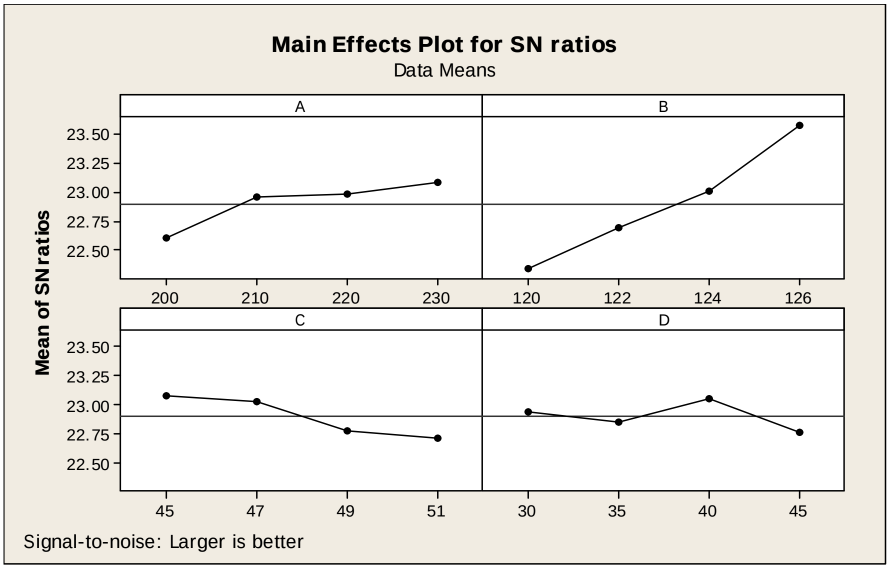

Fig.4. Main Effect Plot for S/N ratio (MRR)

It is clear from the above figures 3 and 4 that the material removal rate highly increases with the increase of pulse on time and peak current, and decreases with increase in pulse off time and little variation with servo voltage, the reason behind this is that the discharge energy increases with the increase of pulse on time and peak current leading to a faster cutting rate. With the decrease in the pulse off time, the number of discharges within a given period becomes more which leads to a higher material removal rate. The effect of servo voltage on cutting rate is not very significant.

The Tables 6 and 7 show ANOVA for means and S/N ratio, as shows below;

Table6: Analysis of variance for Means

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	3	1.42202	1.42202	0.47401	55.29	0.004
Pulse on time	3	8.77642	8.77642	2.92547	341.25	0.000
Pulse off time	3	1.10527	1.10527	0.36842	42.95	0.006
Servo voltage	3	0.48712	0.48712	0.16237	18.94	0.019
Error	3	0.02572	0.02572	0.00857		
Total	15					

Table7: Results of Variance for S/N ratio

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	3	0.51859	0.51859	0.17186	72.38	0.003
Pulse on time	3	3.28958	3.28958	1.09653	459.12	0.000
Pulse off time	3	0.38818	0.31818	0.12939	54.18	0.004
Servo voltage	3	0.17026	0.17026	0.05675	23.76	0.014
Error	3	0.00717	0.00717	0.00239		
Total	15	4.37376				

S = 0.0925900   R-Sq = 99.78%   R-Sq(adj) = 98.91%

2) Response Tables for SR

The Tables 8 and 9 show response for means and Signal to Noise Ratios.

Table8:Response Table for S/N Ratios (SR)
(Smaller is better)

Level	Current(A)	Pulse on time(B)	Pulse off time(C)	Servo voltage(D)
1	-11.63	-11.24	-12.18	-12.05
2	-12.07	-11.72	-12.15	-11.93
3	-12.11	-12.21	-11.84	-12.13
4	-12.19	-12.83	-11.83	-11.83
Delta	0.56	1.59	0.35	0.25
Rank	2	1	3	4

Table 9: Response Table for Means (SR)

Level	Current(A)	Pulse on time(B)	Pulse off time(C)	Servo voltage(D)
1	3.820	3.648	4.080	4.018
2	4.027	3.858	4.063	3.963
3	4.037	4.082	3.915	4.055
4	4.085	4.383	3.913	3.935
Delta	0.265	0.735	0.167	0.120
Rank	2	1	3	4

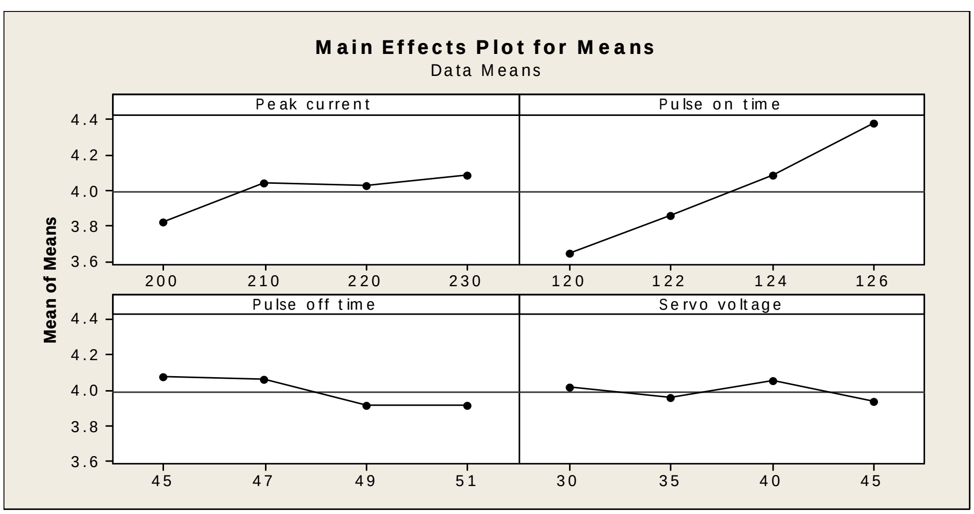

Fig.5: Main Effect Plot for Means (SR)

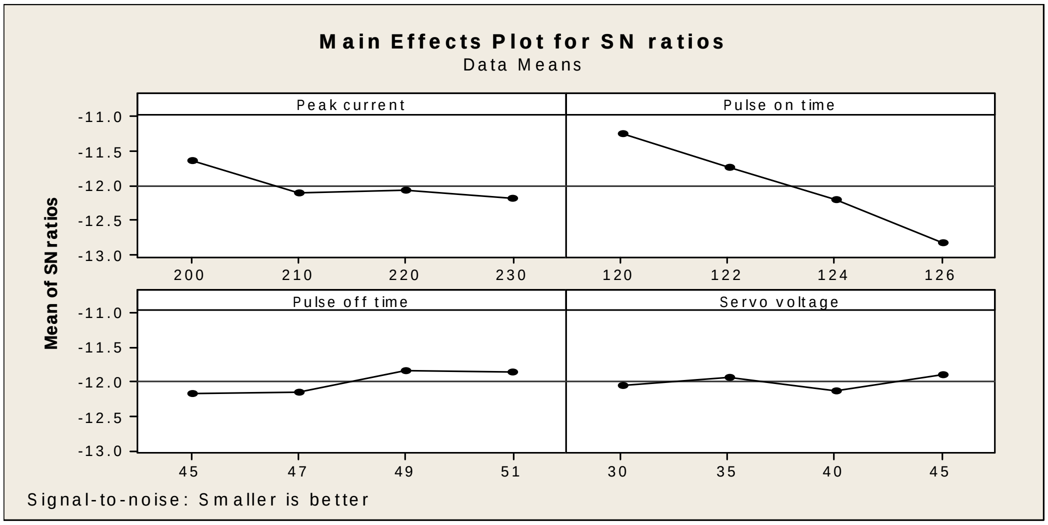

Fig.6: Main Effect Plot for S/N Ratios (SR)

The effects of process parameters for SR are shown from Fig. 5 and Fig. 6 as shown above.

The ANOVA Tables [10,11] for means and s/n ratios are as shown below.

Table 10: Analysis of Variance for S/N Ratios (SR)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	3	0.89147	0.89147	0.29716	6.22	0.084
Pulse on time	3	6.64930	6.64930	2.21643	46.36	0.005
Pulse off time	3	0.33733	0.33733	0.11244	2.35	0.250
Servo voltage	3	0.05115	0.05115	0.01705	0.36	0.790
Error	3	0.14342	0.14342	0.04781		
Total	15	8.07267				

S = 0.218649   R-Sq = 98.22%   R-Sq(adj) = 91.12%

Table 11: Analysis of Variance for Mean2

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	3	0.22845	0.22845	0.07615	7.53	0.066
Pulse on time	3	1.68875	1.68875	0.56292	55.64	0.004
Pulse off time	3	0.09305	0.09305	0.03102	3.07	0.191
Servo voltage	3	0.01180	0.01180	0.00393	0.39	0.771
Error	3	0.03035	0.03035	0.01012		
Total	15	2.05240				

IV. PREDICTION OF OPTIMUM RESPONSE CHARACTERISTICS

A. Metal Removal Rate (MRR)

In this study the optimal value of material removal rate and surface roughness are predicted.

The optimum value of material removal Rate (MRR) is predicted at the optimal levels of significant variables which have already been selected as peak current (A4), peak pulse on time (B4), pulse off time (C1), servo voltage (D3).

These optimal values are presented with their respective confidence intervals. The results of confirmation experiments are done with to validate the estimated optimal results. The values of MRR obtained through confirmation experiments are within the 95% of

CICE of respective response characteristic. It is to be pointed out that these optimal values are within the specified range of process variables.

The estimated mean of the response characteristic (MRR) can be determined as:

$\mu_{MRR} = \{(A4 + B4 + C1 + D3) - 3(\mu)\}$

$= \{(14.29+15.10+14.30+14.13) - 3(13.987)\}$

$= 57.82-41.961 = 15.859$ mm

Where μ = overall mean of material removal rate = $(\Sigma R)/16 = 13.987$.

B. Surface Roughness (SR)

The optimum value of surface roughness (SR) is predicted at the optimal levels of significant variables which have already been selected as taper angle (A2), peak current (B1), pulse on time (C4), pulse off time (D4). The estimated mean of the response characteristic (MRR) can be determined as:

$\mu_{SR} = \{(A_2 + B_1 + C_4 + D_4) - 3\mu\}$

$= (4.037 + 3.648 + 3.913 + 3.935) - (3 \times 3.99)$

$= 15.533 – 11.97$

$= 3.563$ µm

Where $\mu = \Sigma R_1/16 = 3.99$,

And R_1 values are taken from table 2 and A_2, B_1, C_4, D_4 are from table ANOVA.

The Table12 shows predicted optimal values, confidence intervals and results of confirmation experiments

Table 12:Optimal Values of Individual Machining Characteristics

Response	Optimal Set of Parameters	Predicted Optimal Value	Average value of Confirmation Experiment
MRR	A4,B4,C1,D3	15.859	16.000
SR	A1,B1,C4,D4	3.563	3.54

V. OPTIMIZATION OF MULTI-MACHINING CHARACTERISTICS USING GREY RELATIONAL ANALYSIS

To find the optimization of MRR and SR simultaneously using grey relational analysis (GRA), the following steps were followed:

1) Convert the experimental data into S/N values,
2) Normalize the S/N ratio,
3) Perform the grey relational generating and calculate the grey relational coefficient,
4) Calculate the grey relational grade by using the weighing factor for the performance characteristics,
5) Analyzing the experimental results with grey relational grade and statistical analysis of variance (ANOVA)
6) Select the optimal levels of process parameters,
7) Conduct the confirmation experiment to verify the optimal process parameter settings.

Table 13: The Sequence after Data Pre-Processing

Sr. NO.	MRR	SR
Reference sequence	1.00000	1.00000
1	0.02466	0.95860
2	0.16293	0.81370
3	0.29714	0.65559
4	0.54022	0.44840
5	0.29214	0.68470
6	0.33010	0.61707
7	0.39527	0.47602

8	0.64998	0.26086
9	0.00000	1.00000
10	0.27394	0.66528
11	0.55419	0.35793
12	0.85619	0.09880
13	0.58105	0.91607
14	0.33000	0.61707
15	0.50700	0.37580
16	1.00000	0.00000

A. Grey Relational Analysis

Grey data processing must be performed before calculating the grey correlation coefficients.

In this work, a linear normalization of the experimental results (S/N ratios) for MRR and SR were performed in the range of 0 and 1, which is also called the grey relational generating. A linear data pre-processing method for the S/N ratio can be expressed as follows,

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

Where $x_i^*(k)$ is the sequence after the data processing; $x_i^o(k)$ is the original sequence of S/N ratio,

i =1,2………..n with m=16

max. $x_i^*(k)$ said as largest of $x_i^*(k)$; and min $x_i^*(k)$ said as the smallest $x_i^*(k)$.

Table 13 shows the normalized S/N ratios for MRR and SR.

The outcomes are denoted as $x_o^*(k)$ and $x_i^*(k)$for reference sequence and comparability sequence, respectively. Normally, the larger normalized S/N ratio corresponds to the better performance and the best-normalized S/N ratio is equal to unity.

Next, the grey relational coefficient was calculated to express the relationship between the best (reference) and the actual normalized S/N ratio. The grey relational coefficient is expressed as follows

$\Upsilon(x_o^*(k).x_i(k)) =$

$(\Delta_{min} + \zeta.\Delta_{max}) / (\Delta_{oi}^{(k)} + + \zeta.\Delta_{max})$

And

$\Upsilon(x_o^*(k).x_i(k)) \leq 1$

Where $\Delta_{oi}^{(k)}$is the deviation sequence of reference sequence $x_o^*(k)$.and comparability sequence $x_i(k)$.

,i.e$\Delta_{oi}^{(k)} =| x_o^*(k) - x_i(k) |$ is the absolute value of difference between $x_o^*(k)$and$x_i(k)$.

And also

Δ_{min}= min. min. $\Delta_{oi}^{(k)}$

Δ_{max}= max. max. . $\Delta_{oi}^{(k)}$

ζ is the distinguishing coefficients $\zeta \in | 0,1|$.Nowζ is setas0.5in this work. The aim of defining that coefficient is to see the relation al degree between the reference sequences $x_o^*(k)$and the comparability of 16 sequences $x_i(k)$ where i=1,2,3….,m and k=1,2,….,n with m=16andn=2inthisstudy.

$\Delta_{o1}^{(1)}$ = |1.0000-0.02466| = 0.97534

$\Delta_{o1}^{(2)}$=|1.0000-0.95860| = 0.04140

Table 14: The Deviation Sequences

Deviation sequence	Δ_{01}(MRR)	Δ_{02}(SR)
No. 1	0.97534	0.04140
No. 2	0.83062	0.18630
No. 3	0.70285	0.34441
No. 4	0.45978	0.55160
No. 5	0.70786	0.31530

No. 6	0.66990	0.38293
No. 7	0.60473	0.52398
No. 8	0.35002	0.73914
No. 9	1.00000	0.00000
No. 10	0.72606	0.33472
No. 11	0.44581	0.64207
No. 12	0.14380	0.90120
No. 13	0.41895	0.08393
No. 14	0.67000	0.38293
No. 15	0.49300	0.62420
No. 16	0.00000	1.00000

The same calculating method was performed for i=1-16,and the results of all $\Delta_{oi}$for$i$=1-16are listed in Table 14. Investigating the data presented in Table14,we can findthat$\Delta_{max}(k)$and $\Delta_{min}(k)$areas follows;

$\Delta_{max} = \Delta_{16}$ =1.00000

$\Delta_{min} = \Delta_{09}$= 0.000000

$\Upsilon (x_o^* (1).x_1 (1))$ = (0.0000 + 0.5× 1.0000) / (0.97534 + 0.5× 1.0000) =0.33890, and

$\Upsilon (x_o^* (2).x_2(2))$ =(0.0000 + 0.5× 1.0000) / (0.04140 + 0.5× 1.0000) =0.99178

Thus $\Upsilon (x_o^* (k).x_i(k))$ = (0.33890,0.99178)

For k=1-2

Similar procedure is applied for$i$=1-16and the results are summarized inTable15.

The grey relational grade is a weighting-sum of the grey relational coefficients. The overall evaluation of multiple performance characteristics was based on the grey relational grade and it can be defined as follows**;**

$\Gamma (x_o^*.x_i) = \sum_{k=1}^{n} (xo* \ (k).xi(k)ßk$,

Where $ß_k$ represents the weighting value of the kth performance characteristics, and$\sum_{k=1}^{n}$ ßk=1

Using the same weighting values of MRR and SR as were assigned in utility analysis (i.e.w1=w2=0.5),grey relational grade $\Gamma (x_o^*.x_i)$ is calculated as depicted inTable15.

Table 15: The Calculated Grey Relational Coefficient for L16 Comparability Sequences

No.(Comprability sequence)	MRR	SR	Grey relational grade
1	0.33890	0.99178	0.66534
2	0.37395	0.72850	0.55122
3	0.41567	0.59210	0.50388
4	0.52095	0.47546	0.49820
5	0.41395	0.61320	0.51357
6	0.42738	0.56639	0.49683
7	0.45259	0.48829	0.47044
8	0.58820	0.40350	0.49585
9	0.33333	1.00000	0.66650
10	0.44400	0.59900	0.52150
11	0.52864	0.43780	0.48320
12	0.77660	035780	0.56670
13	0.54400	0.85620	0.70010
14	0.42730	0.56629	0.49679
15	0.50350	0.44470	0.47410
16	1.00000	0.33333	0.66650

B. Optimal Level of Process Parameters

Optimization of the multiple performance characteristics can be converted into optimization of single grey relational grade. It is clearly observed from Table15 for grey relational grade, the process parameters setting of experiment no.13 has the highest grey relational grade. Thus, the thirteen no. experiment gave the best multiple performance characteristics among the16 experiments using GRA. For separating out the effect of each process variable on the grey relational grade at different levels, response graph for grey relational grade is constructed using the Taguchi methodology as shown in Fig.7.

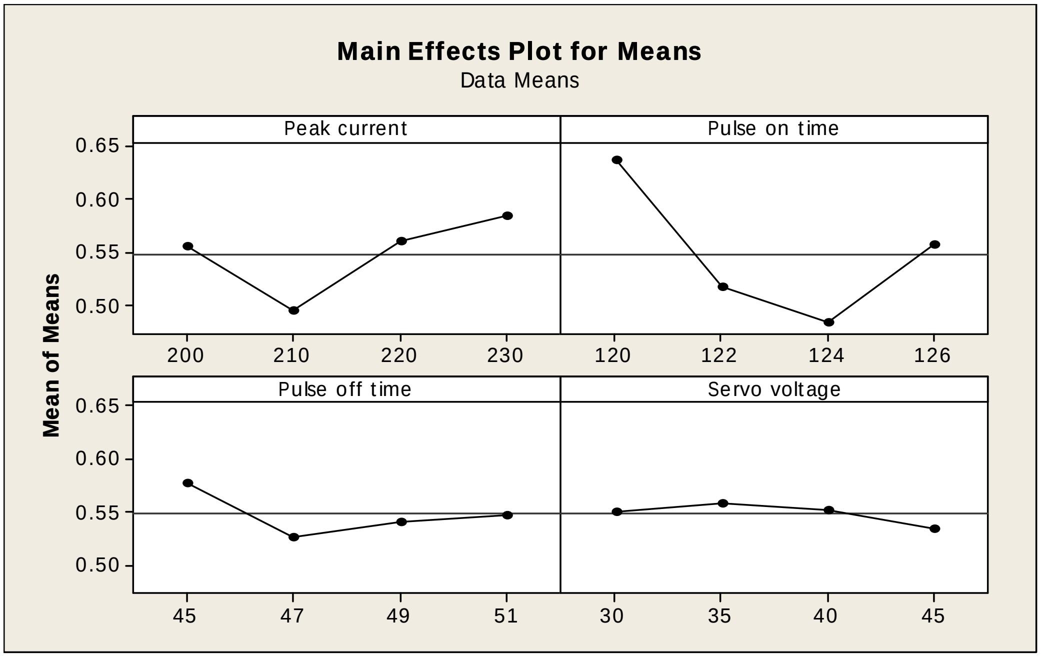

Fig.7-Response graph for mean grey relational grade

Normally, the larger the grey relational grade, the better is the multiple performance characteristics. The combination of $A_4B_1C_1D_2$ shows larger value of the grey relational grade for the factors A, B, C and D, respectively. Therefore, A_4(230 ampere), B_1 (120 µs), C_1(45 µs), D_2(35), is the optimal parameter combination for multi-machining characteristics .The Table16 shows Responses for means for Grey relational grades and Table 17 shows ANOVA for Grey relational grades.

Table 16: Response Table for Means for Grey Relational Grades

Level	Peak Current	Pulse on time	Pulse off time	Servo voltage
1	0.5547	0.6364	0.5780	0.5498
2	0.4942	0.5166	0.5264	0.5576
3	0.5595	0.4829	0.5408	0.5514
4	0.5844	0.5568	0.5476	0.5339
Delta	0.0902	0.1535	0.0516	0.0237
Rank	2	1	3	4

Table 17: ANOVA for Grey Relational Grade

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	3	0.017585	0.017585	0.005862	0.96	0.514
Pulse on time	3	0.052450	0.052450	0.017483	2.85	0.206
Pulse off time	3	0.005669	0.005669	0.001890	0.31	0.820
Servo voltage	3	0.001220	0.001220	0.000407	0.07	0.974
Error	3	0.018373	0.018373	0.006124		
Total	15	0.095298				

C. Predicted Optimal Results

The optimal value of the machining characteristics has been predicted using the same procedure as discussed in previous section. ANOVA results given in Table16 depict that the pulse on time (B) and peak current (A) are the most significant factors affecting the grade values under 95% confidence level. Therefore, only most significant process parameters i.e. B and A have been considered to predict the optimal values of machining characteristics.

D. Confirmation Experiment

To find out the validation the results obtained, three confirmation experiments were conducted for each of the response characteristics (MRR) at optimal levels of the process variables. The average values of the characteristics were obtained and compared with the predicted values. The Table 18 show optimum results obtained by GRA.

Table18:Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments with GRA.

Response	Optimal Set of Parameters	Predicted Optimal Value	Average value of Confirmation Experiment
MRR	A4,B1,C1,D2	13.600	13.000
SR	A4,B1,C1,D2	3.806	3.62

E. Summary of Results

Using Taguchi method, process parameters were optimized individually for MRR and SR. Therefore, process parameters are successfully optimized for individual characteristics using Taguchi method. The optimal setting of process parameters for multiple machining characteristics, using GRA is A4, B1, C1, D2.Using ANOVA, two process parameters namely pulse on time (B), peak current (A) were found significant affecting the grey relational grade, significantly. Therefore, using GRA, process parameters can be successfully optimized for multiple machining characteristics during WEDM of Al Alloy 6061. Table19 summarizes the results for individual and multiple machining characteristics.

Table19: Summary and Comparisonof Results

Method	Optimization technique	Optimal parameters Combination	Predicted optimal Value
Individual characteristics optimization	Taguchi method	A4,B4,C1,D3(MRR) A1,B1,C4,D4(SR)	MRR=15.859 SR=3.563
Multiple characteristics optimization	Grey relational analysis	A4,B1,C1,D2	MRR=13.600 SR=3.806

VI. CONCLUSIONS

In this study, Grey relational analysis (GRA) along with Taguchi method was used to optimize the material removal rate (MRR) and surface roughness (SR) for Al alloy 6061. Based on the results and discussions, the following conclusions are made:

A. Using Taguchi method, MRR and SR were optimized individually. Two different optimal settings of process parameters were found for MRR and SR. The optimal predicted values for MRR and SR are 15.859 mm^3/min. and 3.563 µm.

B. Two process parameters namely pulse-on time(T_{on})and Peak current(I_P) are found the most significant affecting the MRR and SR.

C. In case of GRA, grey relational grade was used as a performance index to determine the optimal combination of process parameters for multiple machining characteristics. In this study, the equal weights were assigned to both the machining characteristics in calculating the grey relational grade. However, with a different set of weights, a different set of optimal parameters for machining characteristics will result.

D. Using GRA, process parameters can be successfully optimized for multiple machining characteristics during WEDM of Aluminium Alloy 6061. The optimal combination of the process parameters, using GRA for multi-machining characteristics is set toA_4 (230 ampere), B_1 (120 µs), C_1 (45 µs), D_2 (35 V).

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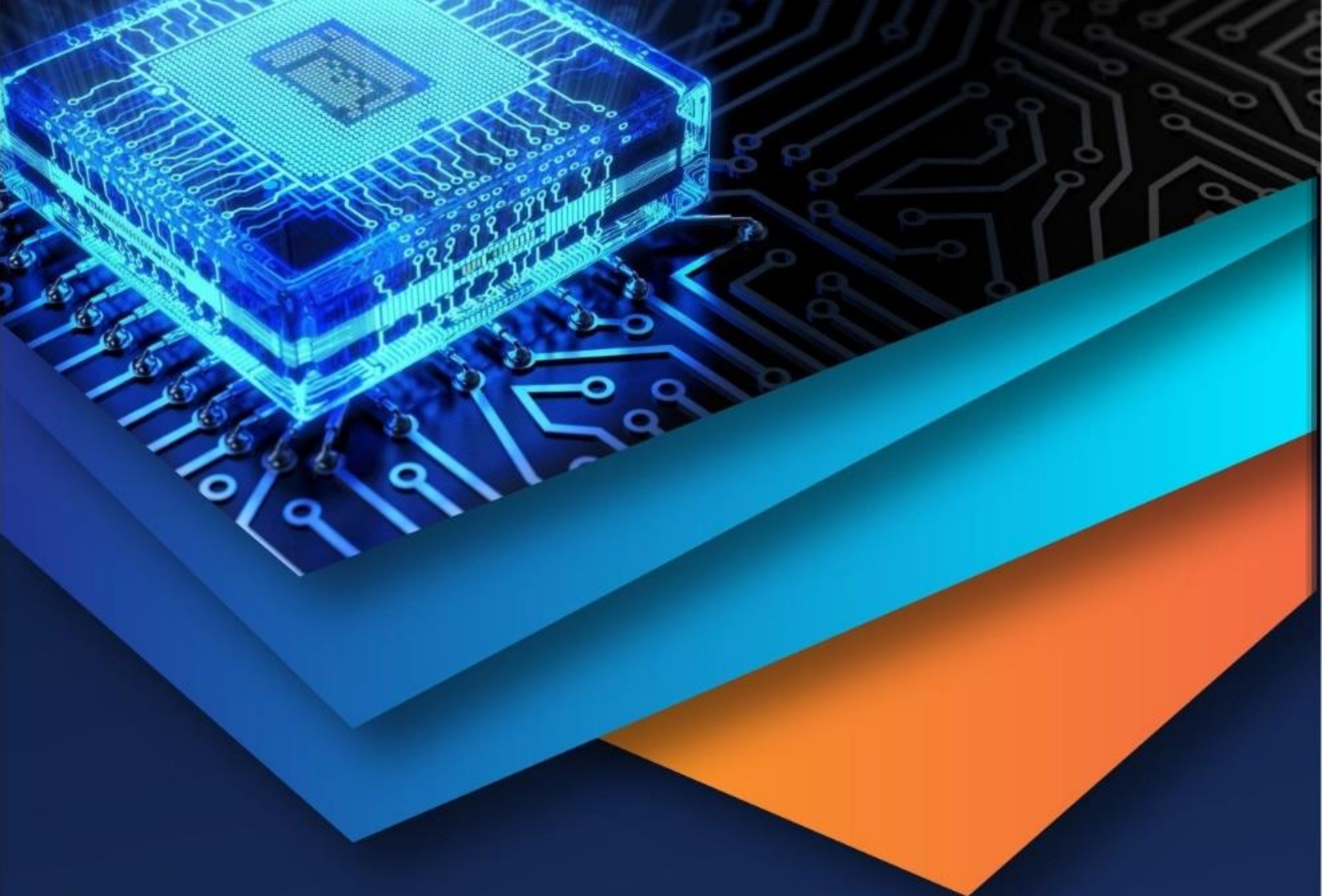

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