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Parameters Optimization on Abrasive Water Jet Machining of Zerconia Ceramics

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Abstract: Ceramic materials play a vital role in industries for several reasons, owing to their unique combination of properties such as high temperature resistance, high wear and abrasion resistance and electrical insulation. Conducting experiments on an abrasive water jet machine involves manipulating three input parameters at three levels each. The parameters are water pressure (1.5 bar, 2.5 bar, and 3.5 bar), standoff distance (4 mm, 8 mm, and 12 mm), and abrasive flow rate (6 gm/sec, 12 gm/sec, and 18 gm/sec).

The responses measured are material removal rate (MRR) and surface roughness (Ra). To systematically study the impact of these parameters the Design of Experiments (DOE) methodology is employed utilizing the L_9 Orthogonal Array (OA) to streamline the experimental design.

The Taguchi technique is then applied to predict the optimal process parameters. For a comprehensive analysis of Variance (ANOVA) is employed to quantify the percentage contribution of each input parameter to the responses shedding light on their relative significance.

Additionally the regression coefficient (R^2) is assessed to gauge the degree of agreement between the experimental and predicted values for the responses.

Keywords: ANOVA, DOE, ZrO_2, Water Jet Machine

I. INTRODUCTION

Zirconium oxide, commonly known as zirconium (ZrO_2) is a remarkable ceramic material that has garnered significant attention across industries due to its exceptional combination of properties. Formed from the chemical bonding of zirconium and oxygen atoms, zirconium exhibits a crystalline structure that can vary from cubic to tetragonal or monoclinic [1] each configuration offering distinct characteristics. With its high melting point [2], impressive mechanical strength, chemical inertness and biocompatibility, zirconium oxide has found myriad applications in fields as diverse as aerospace, biomedicine, electronics, and industrial manufacturing [3].

The abrasive water jet machine represents a cutting edge technology that revolutionizes the precision cutting and shaping of materials [4] across various industries. Harnessing the power of high pressure water streams infused with abrasive particles [5] this cutting system offers unparalleled versatility accuracy and efficiency in processing a wide range of materials, from metals and composites to stone and ceramics [6].

The Taguchi Method, developed by Dr. Genichi Taguchi is a powerful statistical approach to design optimization and quality improvement in manufacturing processes [7]. This methodology rooted in experimental design and robust engineering principles, aims to minimize variation and optimize performance by identifying and controlling key factors that influence product quality and performance [8].

ANOVA, or Analysis of Variance, is a statistical method used to analyze the differences among group means in a sample [9]. It is a powerful tool for comparing the means of three or more groups and determining whether there are statistically significant differences between them.

ANOVA is widely used in various fields such as psychology, biology, economics, and social sciences to compare the effects of different treatments or interventions on a dependent variable [10].

II. EXPERIMENTATION AND METHODOLOGY:

Size of the Specimen 50*50*5 mm

Experiment conducted on abrasive water jet machine on zerconia ceramic materials

Fig.1 ZrO_2 Specimens before machining

Fig.2 Abrasive water jet machine experimental setup

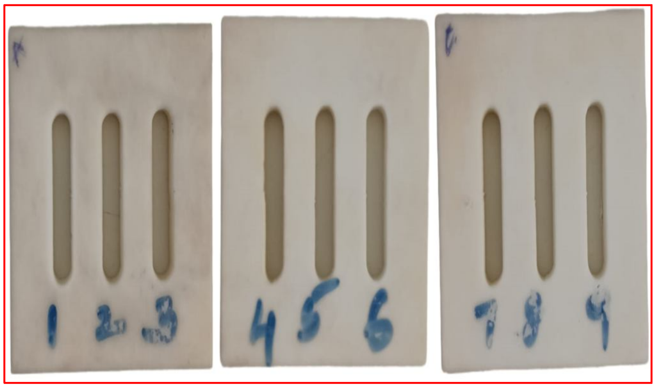

Fig.3 Specimens after machining

Fig.4 Digital Weighing Machine

Fig.5 Surface Roughness Tester

Table 1: Input Parameters and their levels

S. No.	Factors	Unit	Level 1	Level 2	Level 3
1.	Pressure	bar	1.5	2.5	3.5
2.	Standoff Distance	mm	4	8	12
3.	Abrasive flow rate	gm/Sec.	6	12	18

Table: 2 L_9 Orthogonal Array

Exp. No.	Process Parameters		
	Pressure (bar)	SOD (mm)	AFR (gm/Sec.)
1	1.5	4	6
2	1.5	8	12
3	1.5	12	18
4	2.5	4	12
5	2.5	8	18
6	2.5	12	6
7	3.5	4	18
8	3.5	8	6
9	3.5	12	12

Table: 3 Weight of the specimen before and after machining

Sl. No.	Parameters			Initial Weight (g)	Final Weight (g)	Time (Min)
	Pressure (bar)	SOD (mm)	AFR (gm/Sec.)			
1	1.5	4	6	48	47.493	3.16
2	1.5	8	12	47.493	46.76	3.01
3	1.5	12	18	46.76	46.02	3
4	2.5	4	12	48	47.24	3.3
5	2.5	8	18	47.24	46.51	3.18
6	2.5	12	6	46.51	45.83	3.13
7	3.5	4	18	48	47.16	3.3
8	3.5	8	6	47.16	46.55	3.05
9	3.5	12	12	46.55	45.71	2.98

III. RESULTS AND DISCUSSION

Table: 4 Material Removing Rate (MRR) and S/N Ratio of MRR

Sl. No.	Parameters			Measured MRR (gm/Min.)	Means	S/N Ratio
	Pressure (bar)	SOD (mm)	AFR (gm/Sec..)			
1	1.5	4	6	0.160400	0.160400	-15.8959
2	1.5	8	12	0.243889	0.243889	-12.2562
3	1.5	12	18	0.245556	0.245556	-12.1970
4	2.5	4	12	0.228000	0.228000	-12.8413
5	2.5	8	18	0.228095	0.228095	-12.8377
6	2.5	12	6	0.217273	0.217273	-13.2599
7	3.5	4	18	0.252778	0.252778	-11.9452
8	3.5	8	6	0.199286	0.199286	-14.0105
9	3.5	12	12	0.280000	0.280000	-11.0568

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Table 5: Response table for S/N Ratio of MRR

Level	P	SOD	AFR
1	-13.45	-13.56	-14.39
2	-12.98	-13.03	-12.05
3	-12.34	-12.17	-12.33
Delta	1.11	1.39	2.34
Rank	3	2	1

The material removal rate is influenced by various parameters as depicted in Table 7. Analyzing the Abrasive Flow Rate (AFR) parameter reveals that the maximum Signal-to-Noise (SN) ratio value occurs at the third level (-12.33 dB), while the minimum SN ratio value is observed at level 1 (-14.39 db). The resulting delta value, representing the difference between the maximum and minimum is 2.34 dB. Consequently AFR emerges as the most impactful parameter (Rank 1) when compared to the other two input parameters. Standoff distance, the second parameter, demonstrates a maximum SN ratio at level 3 (-12.17 db) and a minimum SN ratio at level 1 (-13.56 db), with a delta value of 1.39 dB (Rank 2). In contrast pressure is identified as the least impactful parameter on the material removal rate, with a delta value of 1.11 db highlighting its minimal influence.

Table 6: Response Table for Means

Level	P	SOD	AFR
1	0.2166	0.2137	0.1923
2	0.2245	0.2238	0.2506
3	0.2440	0.2476	0.2421
Delta	0.0274	0.0339	0.0583
Rank	3	2	1

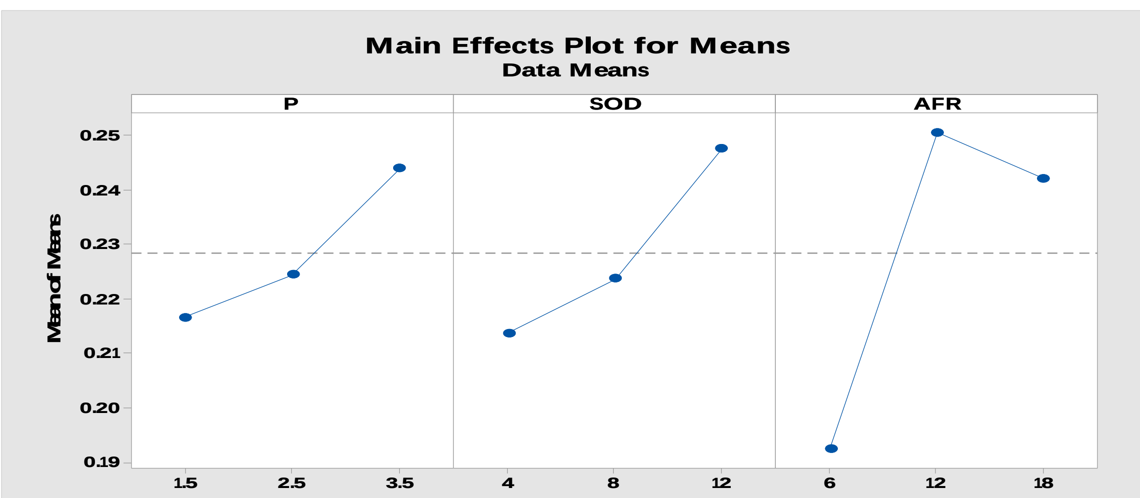

Fig.6 Main effects plots for means

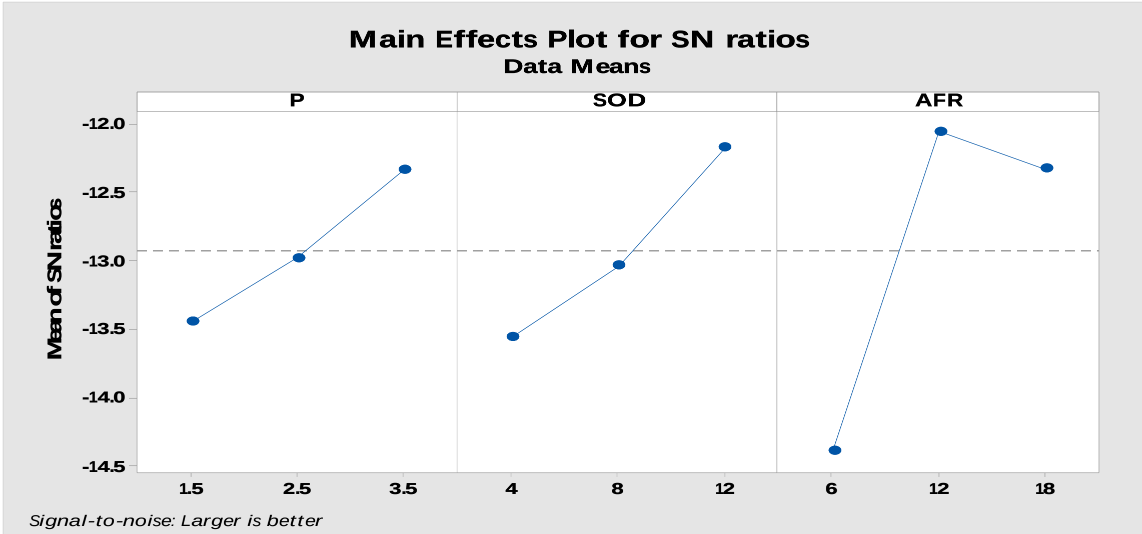

Fig.7 Main Effects plots for S/N Ratio

Examining the connection between the means of Material Removal Rate (MRR) and the input parameters, as illustrated in Figure 16, reveals distinct patterns. When the pressure is elevated from 1.5 rpm to 3.5 bar there is a gradual increase in material removal. Similarly, as the standoff distance expands from 4 mm to 12 mm, the response value also exhibits a progressive rise. Finally as the abrasive flow rate (AFR) is increased from 6 mm to 12 mm, the response value experiences a sudden surge. However a further increase in AFR leads to a sudden decrease in the material removal rate.

The correlation between input parameters and the Signal-to-Noise (SN) ratio of the Material Removal Rate (MRR) is depicted in Figure 17. When the pressure is elevated from 1.5 bar to 3.5 bar there is a sudden increase in the SN ratio. Similarly, as the standoff distance expands from 4 mm to 12 mm, the SN ratio also experiences a sudden surge. Lastly, when the abrasive flow rate (AFR) is increased from 6 mm to 8 mm, the SN ratio rises abruptly. However, with a further increase in AFR, the SN ratio gradually declines

Table. 7 Optimum Parameters

Sl. No	Input Parameters	Unit	Optimum level	Value
1	Pressure (P)	bar	3	3.5
2	Standoff distance (SOD)	mm	3	12
3	Abrasive flow rate (AFR)	gm/min	2	12
Optimum SN Ratio: -11.0568 (0.280000db) Experimental SN ratio: -10.7156 (0.285532 db) Improvement SN Ratio:0.3412 (0.005532 db)				

After selecting the optimum cutting parameters, the final step is checked and determines the improvement of MRR (g/sec.) to predict and verify the optimization by using the optimum level machining parameters the experimentation was once again performed at P_3, SOD_3, AFR_2 The parametric combination for maximum MRR (g/sec) was observed at Pressure (P=3.5 bar), Standoff distance (SOD= 12 mm), and finally Abrasive flow rate (AFR = 12g/min) respectively.

Table. 8 Analysis of Variance of MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
P	2	0.001195	0.000598	2.85	0.260	12.7
SOD	2	0.001818	0.000909	4.34	0.187	19.36
AFR	2	0.005954	0.002977	14.20	0.066	63.42
Error	2	0.000419	0.000210	-	-	4.4
Total	8	0.009387	-	- -		

R^2 = 95.53% R^2 (adj) = 82.13

At a 99% confidence level the analysis of variance (ANOVA) revealed the percentage contribution of each parameter and error to the material removal rate (MRR). The predominant influence on MRR was attributed to abrasive flow rate, accounting for 63.42%, followed by standoff distance with a contribution of 19.36%, and water pressure at 12.7%, respectively. The regression coefficient of MRR stands at 95.53%, indicating a strong agreement between the measured and predicted values.

Regression Equation

MRR = 0.22836 - 0.01175 P_1.5 - 0.00391 P_2.5 + 0.01566 P_3.5 - 0.01464 SOD_4 - 0.00461 SOD_8 + 0.01925 SOD_12 - 0.03604 AFR_6 + 0.02227 AFR_12 + 0.01378 AFR_18

Table 9. Surface Roughness Measurements

Sl. No.	Parameters			Surface Roughness (Ra)
	Pressure (bar)	SOD (mm)	AFR (gm/Sec.)	
1	1.5	4	6	3.745
2	1.5	8	12	3.695
3	1.5	12	18	3.025
4	2.5	4	12	4.145
5	2.5	8	18	1.075
6	2.5	12	6	1.085
7	3.5	4	18	4.595
8	3.5	8	6	3.135
9	3.5	12	12	2.478

Table.10 Response Table for Signal to Noise Ratios

Level	P	SOD	AFR
1	-10.812	-12.355	-7.367
2	-4.562	-7.302	-10.695
3	-10.518	-6.235	-7.829
Delta	6.250	6.120	3.328
Rank	1	2	3

The surface roughness rate is influenced by various parameters as depicted in Table 7. Water pressure (P) parameter reveals that the maximum Signal-to-Noise (SN) ratio value occurs at the second level (-4.562 db), while the minimum SN ratio value is observed at level 1 (-10.812 dB). The resulting delta value representing the difference between the maximum and minimum is 6.250 dB. Consequently Pressure emerges as the most impactful parameter (Rank 1) when compared to the other two input parameters. Standoff distance the second parameter demonstrates a maximum SN ratio at level 3 (-6.235 db) and a minimum SN ratio at level 1 (-12.355 db) with a delta value of 6.120 db (Rank 2). In contrast abrasive flow rate is identified as the least impactful parameter on the material surface roughness with a delta value of 3.328 db highlighting its minimal influence.

Table.11 Response Table for Means of Surface Roughness

Level	P	SOD	AFR
1	3.488	4.162	2.655
2	2.102	2.635	3.488
3	3.452	2.245	2.898
Delta	1.387	1.917	0.833
Rank	2	1	3

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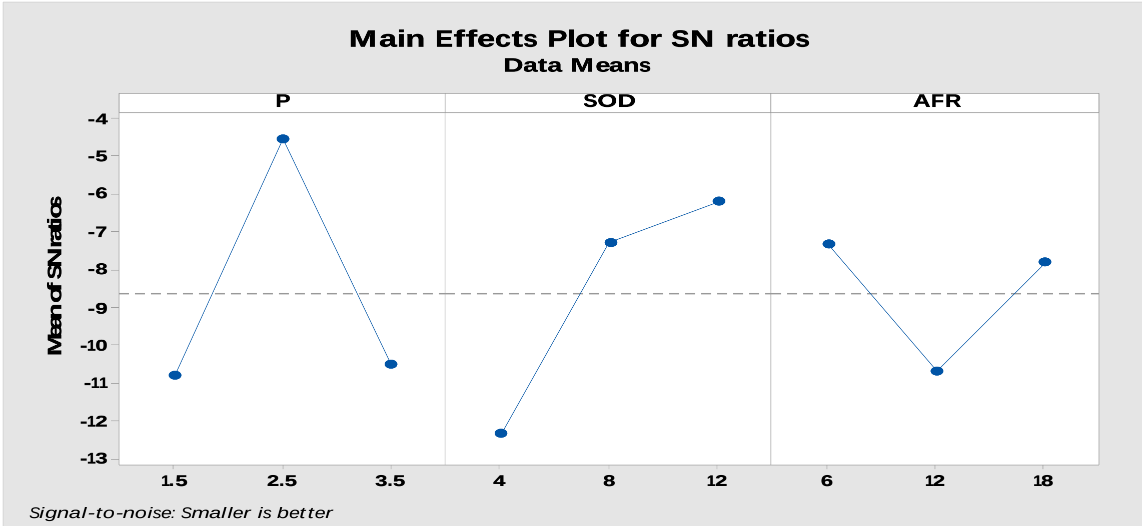

Fig.8 Main effects plots for S/N Ratio

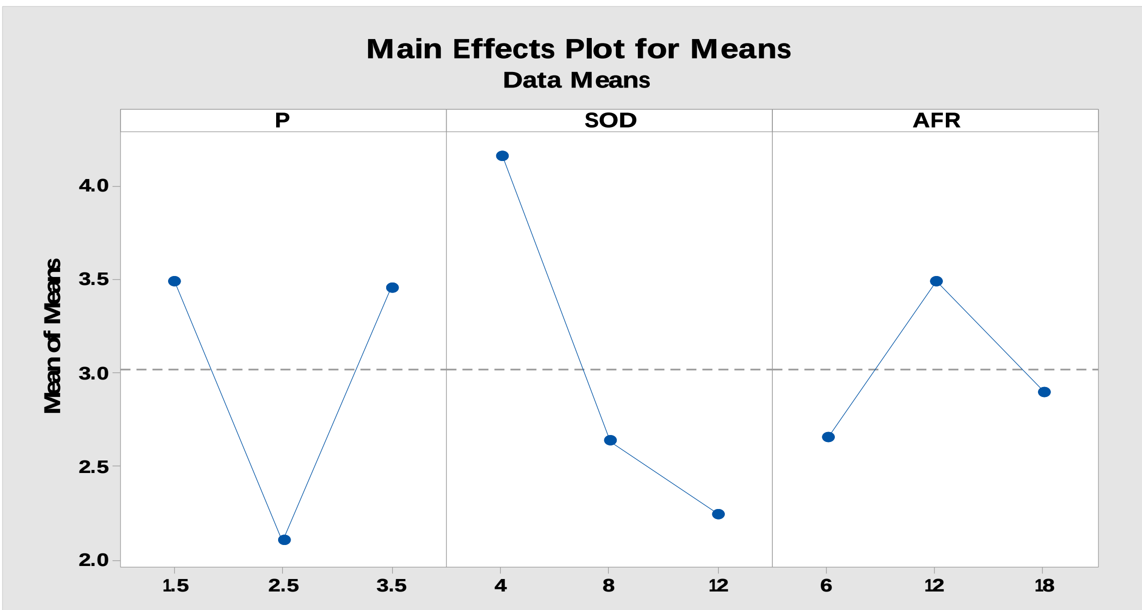

Fig.9 Main effects plot for Means

Analyzing the correlation between the Signal-to-Noise (S/N) ratio of Surface Roughness (Ra) and the input parameters as depicted in Figure 16, unveils distinctive trends. As the pressure ascended from 1.5 bar to 2.5 bar the S/N ratio exhibited a sudden increase however, with a subsequent rise in pressure from 2.5 bar to 3.5 bar, the S/N ratio experienced a sudden decrease. Regarding the relationship between the S/N ratio and standoff distance (SOD) an abrupt surge in the S/N ratio was observed when the SOD increased from 4 mm to 8 mm. With further increments in SOD the S/N ratio exhibited a gradual increase. Finally examining the connection between the Abrasive Flow Rate (AFR) and S/N ratio revealed that as AFR escalated from 6 gm/sec to 12 gm/sec the S/N ratio underwent a sudden decrease. Conversely, upon further elevation of the AFR value the S/N ratio exhibited a sudden increase.

The relationship between input parameters and the surface roughness means is illustrated in Figure 17. Upon increasing the pressure from 1.5 bar to 2.5 bar, there is a sudden decrease in the means. This trend continues with further increments in pressure showcasing a decline in the means of surface roughness. Similarly, as the standoff distance extends from 4 mm to 12 mm, the means experiences a gradual decrease, declining slowly. Finally, when the abrasive flow rate (AFR) is raised from 6 mm to 12 mm, the means shows an abrupt rise. However upon further increasing the AFR the means gradually declines.

Table: 12 Optimum Parameters on Ra

Sl. No	Input Parameters	Unit	Optimum level	Value
1	Pressure (P)	bar	2	2.5
2	Standoff distance (SOD)	mm	3	12
3	Abrasive flow rate (AFR)	gm/min	1	6
Experimental SN ratio: -0.903745 db (0.97388µm) Optimum SN Ratio: -0.7086db (1.085µm) Improvement SN Ratio: 0.1951db (0.112µm)				

Table.13 Analysis of Variance of Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
P	2	3.747	1.8733	2.64	0.275	30.15
SOD	2	6.156	3.0782	4.34	0.187	49.55
AFR	2	1.102	0.5509	0.78	0.563	8.86
Error	2	1.419	0.7094	-	-	11.42
Total	8	12.424	-	-		-

R^2 = 88.58%

Regression Equation of Ra

Ra = 3.014 + 0.474 P_1.5 - 0.912 P_2.5 + 0.438 P_3.5 + 1.148 SOD_4 - 0.379 SOD_8 - 0.769 SOD_12 - 0.359 AFR_6 + 0.474 AFR_12 - 0.116 AFR_18

IV. CONCLUSION

The study utilized an L_9 orthogonal array for experimentation. The results showed that all input parameters had probability values for responses that were less than 0.5, indicating their significance on the responses.

ANOVA analysis revealed the percentage contribution of each parameter to the outcomes. For the material removal rate, abrasive flow rate had the highest contribution at 63.42%, followed by standoff distance at 19.36%, and water pressure at 12.7%.

Regarding surface roughness, standoff distance had the most significant contribution at 49.55%, followed by water pressure at 30.15%, and abrasive flow rate at 8.86%.

The regression coefficients (R^2) for material removal rate and surface roughness were found to be 95.53% and 88.58%, respectively, at a 99% confidence level, as confirmed by further testing at the same confidence level. These findings underscore the substantial impact of the input parameters on the studied responses, highlighting the importance of optimizing these parameters for desired

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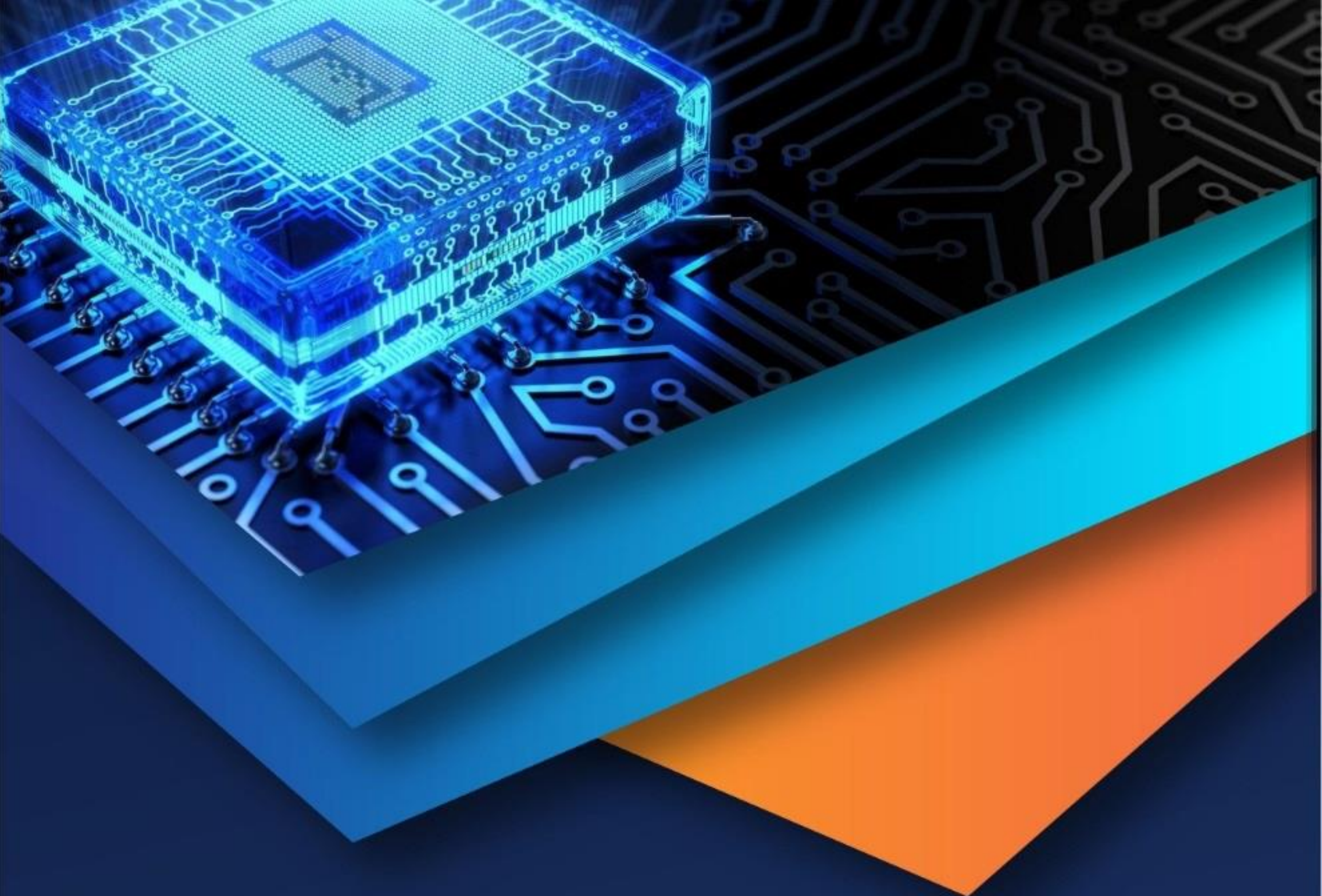

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