iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 **Issue:** VIII **Month of publication:** August 2020

DOI: https://doi.org/10.22214/ijraset.2020.30777

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue VIII Aug 2020- Available at www.ijraset.com

Development of Mathematical Model to Predict Weld Dilution for GMA Welding of Stainless Steel 301

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Abstract: The process of obtaining surfaces with good corrosion resistive properties by coating corrosive surfaces with a layer of anticorrosive metal is called weld cladding. The main purpose of performing cladding process on low carbon steel alloys is to achieve enhanced durability and maximum economy of the components. Due to its various applications, Gas Metal Arc Welding (GMAW) is a widely used welding processes. GMAW has wide spread applications in fabrication industry owing to its ability to provide us with good quality of joints. GMAW is used for cladding process to minimise dilution as low as possible without degrading joint strength. One of the most important things to be considered while performing GMAW process is to select the input welding parameters. Controllable input parameters were selected based on their impact on the output parameter for better understanding. Apart from many output parameters of weld joint one is weld dilution which is governed by provided input parameters. In present work effect of five input parameters (viz. wire feed rate(WFR), welding speed, voltage, nozzle to plate distance(NPD), torch angle) on dilution is investigated.

Keywords: GMA Welding, Dilution, Stainless Steel 301, ANOVA, Design of Experiments, RSM

I. INTRODUCTION

GMAW owning to its numerous advantages has wide applications in the joining industry. Due to its high reliability, low cost to production ratio, capability to weld in all positions and absence of flux due to which there is a low possibility of entrapment of slag and also eliminates the need of post weld cleaning.[1] In the process, an arc is initiated between the plate and a continuously fed electrode, shielded with the help of an inert gas.[2]

As MIG Welding is a multi-input and output process, therefore the quality of the weld determined by the Bead geometry and the presence of minimal detrimental residual stress is influenced by input variables [3][4] Hence, the input parameters are selected and through a series of experiments optimised values of parameters are found. In the present work of research, a mathematical model has been developed to determine the relationship between input variables that are WFR, Voltage, Welding Speed, NPD and Torch Angle and their cumulative effect on the response factor which is Dilution for the present case study.[5] Diagram of weld Bead is given in Fig 1.

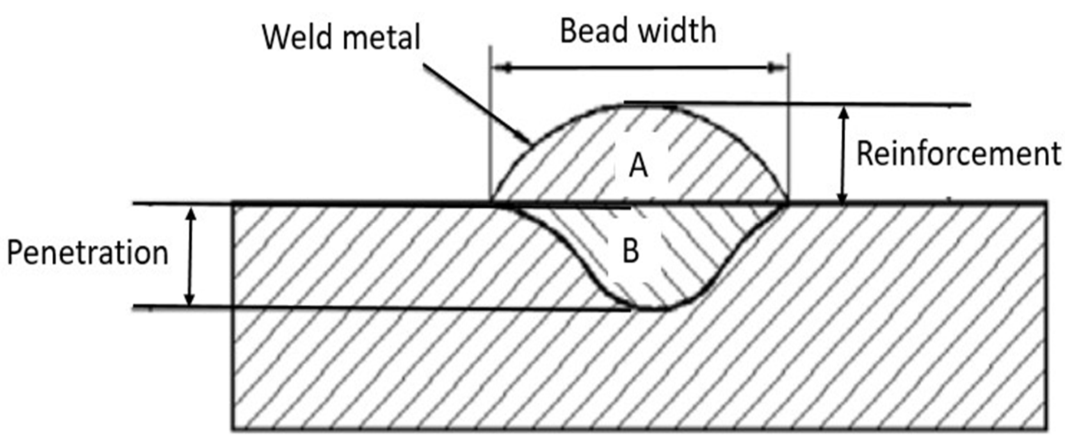

Fig 1 : Diagram of Weld Bead[6]

A : Area of Reinforcement ; B : Area of Penetration

The mechanical attributes and strength of the weld joint highly depend upon the shape and geometry of the bead, with particular regard to the dilution characteristics which are responsible for corrosion-resistant properties, endurance and ductility and effect of heat on the weld.

Dilution can be described as the ratio of area of weld bead penetration and the overall area of the bead.[2]

%Dilution = 100 * (AP / (AR + AP)) [7] ; where AR is the reinforcement area and AP is the penetration area.

Stainless Steel 301 is an austenitic chromium-nickel steel, possessing high corrosion resistance and strength. It also provides adequate weight reduction which makes it useful in various applications.[8] The chemistry of SS 301 is given in table 1.

Table 1 : Chemistry of SS 301[9]

S	**Si**	**P**	**Ni**	**Cr**	**C**	**N**	**Mn**
0.003	0.620	0.027	6.580	17.00	0.100	0.057	0.790

SS301, as compared to SS304, has a lower chromium nickel percentage which provides high tensile strength with lower loss of ductility.[1]

The fed electrode, of austenitic stainless steel 308L, is a consumable, solid core type. The wire used is 1.2 mm thick. The alloy having a low carbon content makes it suitable for applications with a risk of inter-granular corrosion [10]. SS-308L has a lower carbon percentage (0.03%) as compared to SS-308 (0.05%) which makes it fairly more ductile and weldable. The chemistry of the metal are given below in table 2.

Table 2 : Chemistry of SS-308L[11]

Mn	Ni	Si	Cu	Mo	S	P	Cr	C
1-2.5	9-11	0.30-0.65	0.75max	0.75max	0.03max	0.03max	19.5-22	0.03

The mathematical model which is generated assists in predicting the extent of dilution for better weld characteristics or to automate the process for optimised results. [12].

The adequacy of the mathematical model generated has been checked using ANOVA and the results are graphically analysed by response surface methodology (RSM). Response surface methodology (RSM) is a method that establishes and then visualises the relationship between responses and controlled input parameters affecting the output variables as two or three dimensional hyper surfaces.[13]

II. EXPERIMENTAL SET-UP

The apparatus consists of a welding power source of constant voltage type characteristic and the current ranges from 50-400 A and has 100% duty cycle. For shielding the workpiece pure argon gas was used. Austenitic SS308L is used as the composition of the filler wire which has a diameter of 1.2 mm and is continuously fed. The welding power source attached to a welding torch is fixed above the workpiece. The torch can be moved up and down and adjusted at various angles. The speed of the movable carriage holding the workpiece ranges from 0-50 cm/min. The set-up is shown in fig 2.

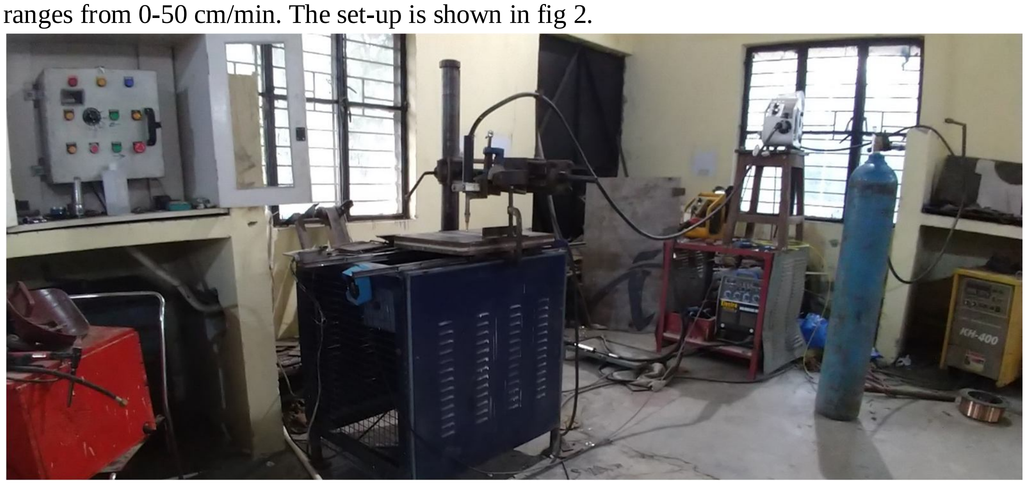

Fig 2 : Experimental Set-Up

III. PLAN OF INVESTIGATION

1) Selection of user-controllable inputs.
2) Estimating the working limits of the user-controlled inputs.
3) The design matrix
4) Conducting the experiments based on the design matrix.
5) Development of the mathematical model.
6) Testing the adequacy of the model.
7) Analysis of the achieved results
8) Conclusions

A. *Selection of User-Controllable Inputs.*

User-controllable input parameters were selected which had the deepest impact on the output parameter, these are torch angle, welding speed, WFR, NPD and voltage.

B. *Estimating the Working Limits of the User-Controlled Inputs.*

The appropriate ranges of the input parameters were ascertained after numerous trial runs by changing one parameter and keeping the rest unchanged. The beads were visibly checked for defects like blow holes, porosity etc. The ranges are categorized into 5 parts in which the extremes were +2 and -2, intermediate ranges were +1 and -1 and the middle range is 0. The working limits of input parameters are shown in table 3.

Table 3 : Working Limits of Input Parameters

Input Parameter	Unit	LEVEL				
		-2	-1	0	1	2
WFR	m/min	0.3	0.6	0.9	1.2	1.5
Voltage	V	14	16	18	20	22
Torch Angle	Degrees	70	80	90	100	110
Welding Speed	cm/min	30	35	40	45	50
NPD	mm	10	12.5	15	17.5	20

C. *The Design Matrix*

The design matrix is generated using the software design of experiments which has determined the interrelationship between input and output parameters. The design matrix is shown in table 4.

Table 4 : Design Matrix

Run	WFR (m/min)	Voltage (V)	Welding Speed (cm/min)	Torch Angle (Degrees)	NPD (mm)	AR (mm^2)	AP (mm^2)	% Dilution (mm/mm)
1	0	0	0	0	0	7.82	14.18	64.43
2	1	-1	-1	1	1	18.17	12.07	39.90
3	1	1	-1	1	-1	13.7	15.3	52.75
4	1	-1	-1	-1	-1	14.08	13.15	48.29
5	0	0	2	0	0	7.25	7.82	51.91
6	0	0	0	0	0	12.77	21.18	62.38

7	2	0	0	0	0	15.12	17.32	53.38
8	-1	1	-1	-1	-1	7.51	6.85	47.70
9	0	0	0	0	0	13.09	15.41	54.07
10	0	0	0	0	-2	10.88	5.46	33.41
11	0	0	0	-2	0	11.82	19.79	62.60
12	0	0	0	0	0	10.45	15.85	60.26
13	0	2	0	0	0	11.14	13.07	53.98
14	1	-1	1	1	-1	9.01	14.77	62.11
15	1	1	-1	-1	1	26.25	17.3	39.72
16	-1	-1	-1	1	-1	11.08	10.89	49.56
17	-1	-1	1	1	1	4.74	4.63	49.41
18	1	-1	1	-1	1	12.46	7.36	37.15
19	0	0	0	0	0	9.14	10.52	53.52
20	-1	-1	-1	-1	1	7.84	4.87	38.32
21	0	0	0	2	0	14.03	17.14	54.98
22	0	-2	0	0	0	6.52	11.46	63.75
23	-1	1	1	1	-1	8.04	11.66	39.88
24	0	0	-2	0	0	11.41	12.82	52.90
25	1	1	1	-1	-1	14.37	12.15	45.81
26	-1	1	-1	1	1	5.88	6.06	50.74
27	0	0	0	0	2	10.09	3.97	28.24
28	-1	1	1	-1	1	3.72	4.16	52.80
29	0	0	0	0	0	9.79	13.19	57.38
30	-1	-1	1	-1	-1	3.93	9.29	70.27
31	1	1	1	1	1	7.97	9.86	55.30
32	-2	0	0	0	0	2.41	1.82	43.12

D. Conducting the Experiments based on the Design Matrix.

A total of 32 trial runs were performed as shown in the table 5. SS301 of 4 mm thickness was used to carry out the experiments. A section of 50 mm x 50 mm was cut from the centre of the weldment and the cross sectional edge was polished by using standard procedure. The specimen was then etched by using a standard etchant. Shadow graphs were used to measure the dimensions of the bead and later the required areas were calculated.

E. Development of the Mathematical Model.

A second degree polynomial equation has been generated where Y is the response parameter and (A,B,C,D,E) are the input parameters

$$Y = f(A,B,C,D,E)$$

The mathematical equations generated is:

Dilution = 58.47 + 0.12*A - 1.24*B + 1.82*C + 0.18*D – 2.64*E + 1.41*AB – 0.39*AC + 3.66*AD – 1.30*AE - 2.50*BC + 0.35*BD + 4.87*BE - 1.14*CD + 0.38*CE + 2.20*DE - 2.40*A^2 + 0.25*B^2 - 1.36*C^2 + 0.23*D^2 - 6.76*E^2.

F. Testing the Adequacy of the Model.

The developed models were then analysed with the help of ANOVA analysis, and the adequacy of the model is given in table 5 and 6. Fig 3 shows the predicted vs actual results.

Table 5 : ANOVA Analysis of the Quadratic Models

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2650.49	20	132.52	4.57	0.0064	significant
A-WFR	0.3523	1	0.3523	0.012	0.91	
B-Voltage	37.12	1	37.12	1.28	0.28	
C-Welding Speed	79.81	1	79.81	2.75	0.12	
D-Torch Angle	0.7824	1	0.7824	0.02	0.87	
E-NPD	167.30	1	167.30	5.77	0.03	
AB	31.88	1	31.88	1.10	0.31	
AC	2.50	1	2.50	0.08	0.77	
AD	214.57	1	214.57	7.40	0.01	
AE	26.90	1	26.90	0.92	0.35	
BC	99.90	1	99.90	3.45	0.09	
BD	2.02	1	2.02	0.06	0.79	
BE	378.82	1	378.82	13.07	0.0041	
CD	20.88	1	20.88	0.72	0.41	
CE	2.42	1	2.42	0.08	0.77	
DE	77.09	1	77.09	2.66	0.13	
A^2	169.32	1	169.32	5.84	0.03	
B^2	1.85	1	1.85	0.06	0.80	
C^2	54.64	1	54.64	1.88	0.19	
D^2	1.59	1	1.59	0.05	0.81	
E^2	1339.98	1	1339.98	46.23	< 0.0001	
Residual	318.84	11	28.99			
Lack of Fit	219.97	6	36.66	1.85	0.25	not significant
Pure Error	98.87	5	19.77			
Cor Total	2969.34	31				

Table 6 : Adequacy of the Model

Std. Dev.	5.38	R^2	0.8926
Mean	50.94	Adjusted R^2	0.6974
C.V. %	10.57	Predicted R^2	-1.0269
		Adeq Precision	9.7490

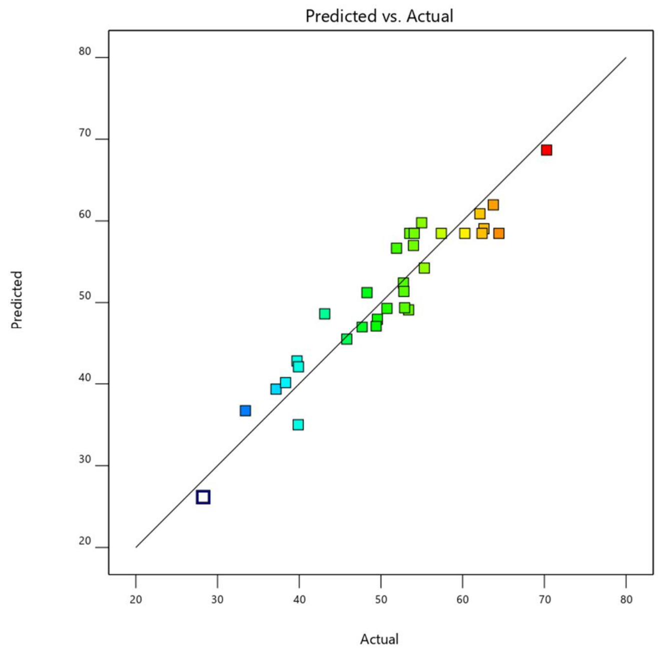

Fig 3 : Actual VS Predicted Results

G. Analysis of the Achieved Results

A detailed graphical result has been analysed in this section to form a relationship between input and output parameters.

1) Combined Effect of NPD and WFR on Dilution

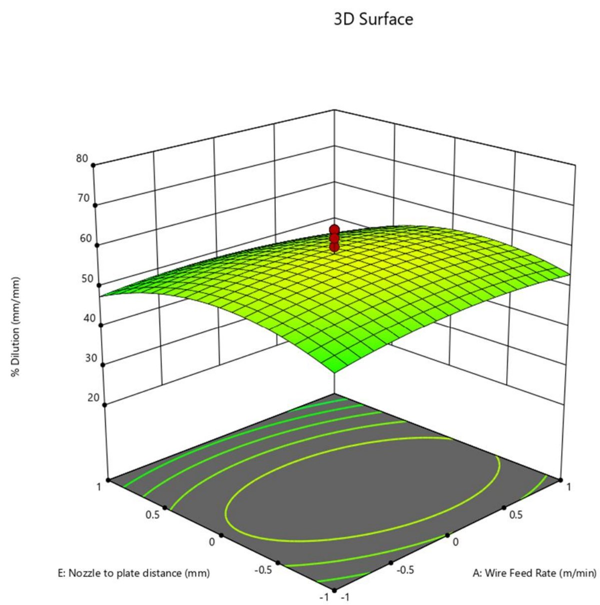

Fig 4 : Combined effect of NPD and WFR on Dilution

Fig 4 depicts that the minimum value of dilution is obtained at maximum NPD and maximum WFR. This shows that at higher WFR an increase in NPD results in a decrease in penetration and an increase in reinforcement. The probable explanation is that when nozzle is at a large distance from the bead plate, it leads to a decrease in heat energy at the bead plate which decreases penetration. However, with an increase in WFR, more filler metal is melted and deposited leading to an accumulation of molten metal at the top yielding a higher reinforcement and hence decreasing dilution.

2) Combined Effects of Torch Angle and WFR on Dilution

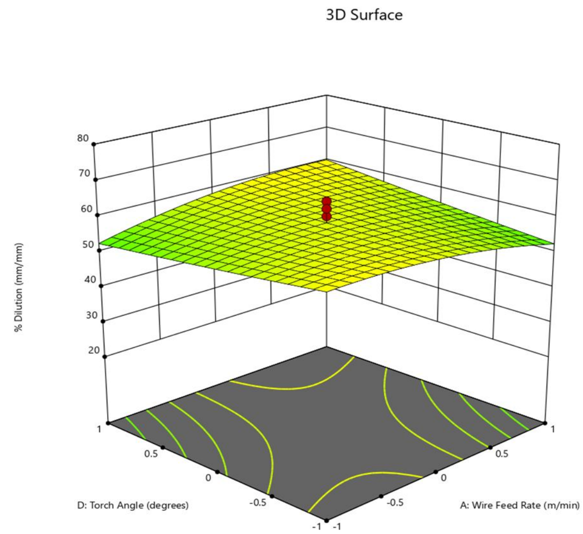

Fig 5 : Combined Effect of Torch Angle and WFR on Dilution.

In fig 5, it can be discerned that at higher torch angles, an increase in WFR yields an increase in dilution which shows that WFR has a more profound effect on dilution than torch angle. The probable reason behind this is as WFR increases, Arc force increases which digs deeper into the base plate increasing the penetration area with consequent increase in dilution.

3) Combined Effect of NPD and Voltage on Dilution.

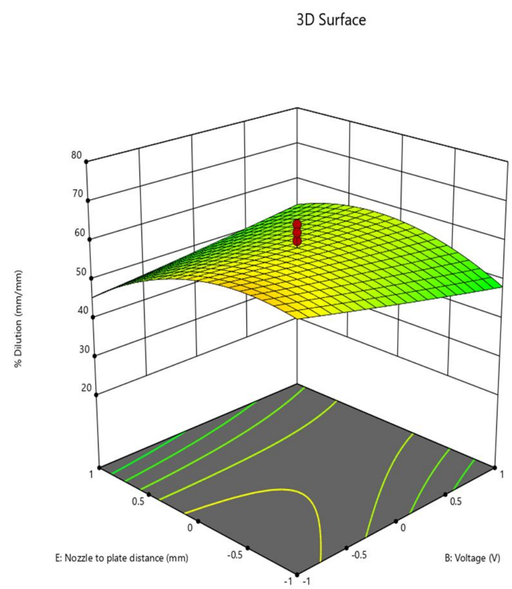

Fig 6 : Combined Effect of NPD and Voltage on Dilution.

Fig 6 depicts that at all the values of NPD it is seen that there is a slight decrease in dilution with increase in voltage. The probable reason is as voltage increases the bead has tendency to get wider rather than deeper with reduction in AP and in present case it seems that there is reduction in AP against the almost constant AP+AR, causing a reduction in dilution. At all values of voltage, there seems to be a significant drop in dilution with an increase in NPD because as NPD increases the reinforcement increases pre-dominantly against P causing decrease in dilution.

4) Combined Effect of NPD and Welding Speed on Dilution.

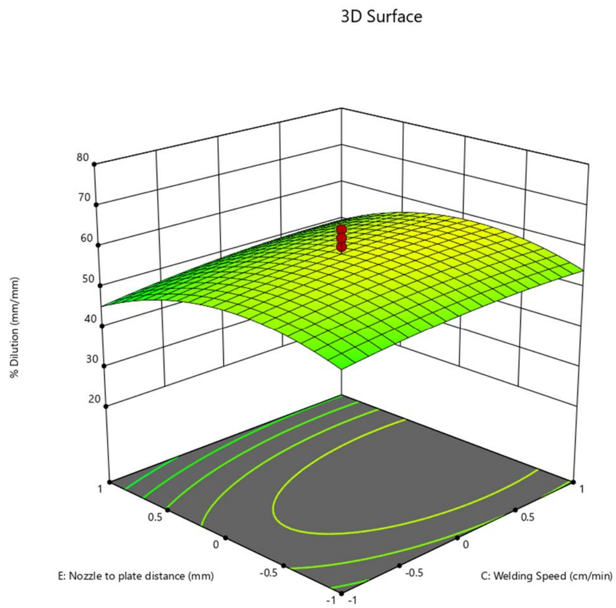

Fig 7 : Combined Effect of NPD and Welding Speed on Dilution.

It can be seen that in Fig 7, welding speed doesn't have a significant effect on dilution in the selected range of parameters however, dilution reduces significantly with increase in NPD for the reason explained in previous section (Combined effect of NPD and WFR on Dilution)

5) Combined Effect of NPD and Torch Angle on Dilution

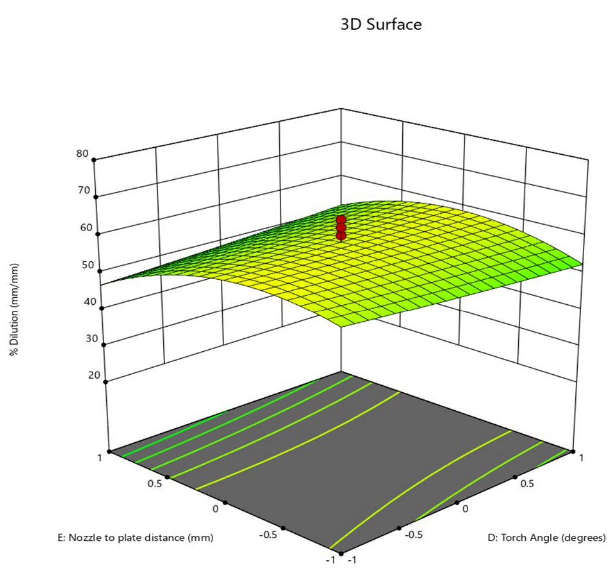

Fig 8 : Combined Effect of Torch Angle and NPD on Dilution

From the fig, it is evident that both NPD and torch angle have a negative effect on dilution. The reason is with the increase in torch angle the arc spreads, causing the bead to spread rather than penetrate, reducing AP and consequently reduced dilution and the effect of NPD is explained in previous section.

IV. CONCLUSIONS

A. Minimum value of dilution i.e., 28.24(# 27) is obtained at the central value of all the parameters and the maximum working limit of NPD.

B. Maximum value of dilution i.e., 70.27 (# 30) is obtained at the intermediate working limit of all the parameters i.e., -1.

C. NPD, Torch angle and voltage have a negative effect on dilution whereas WFR has a positive effect and welding speed having negligible effect on dilution within the selected working limits.

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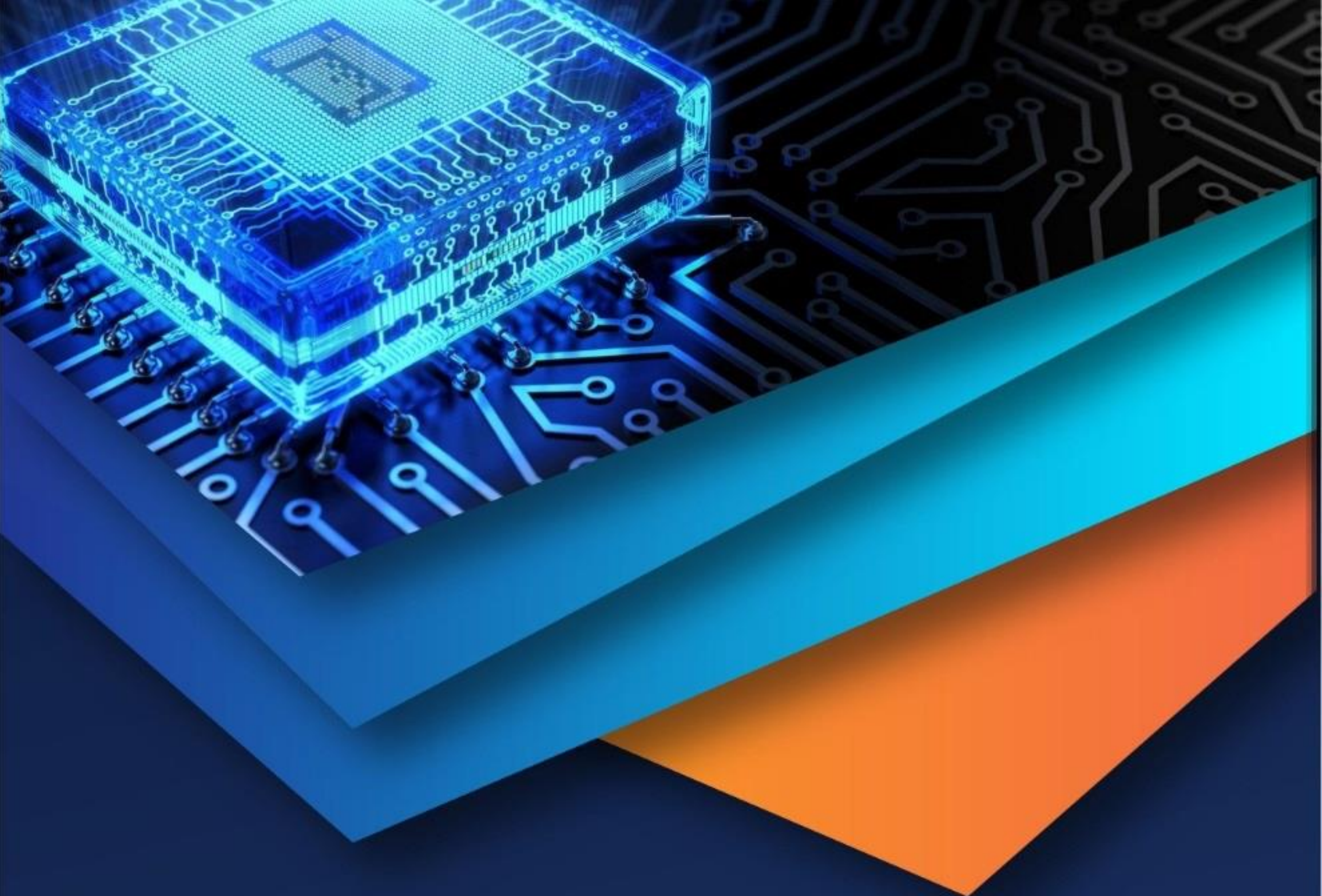

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