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Experimental Investigation and Analysis of Tensile Strength of Dissimilar Friction Welded Joints of Aluminium 6061 and Mild Steel

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Abstract: Nowadays, the joining process plays a vital role in every field of engineering application. Various similar and dissimilar materials are joined by many joining processes to a formed complex component. In all joining processes, welding is a very popular and effective joining process that gives permanent joint. In this process material to be joined is under influence of heat which is produced with aid of external (flame) and internal (friction) mediums. Further, there are types of welding process called friction welding which is solid-state welding, in that process friction had developed between materials having relative motion thus sufficient heat also produced, and welding is performed in solid-state. In recent time's friction welding is widely used in automobile, aeronautical, structural, marine, etc areas due to its flexibility demand for various materials. In this research work, the aluminium 6061 and mild steel are joined by friction welding by varying the rotating speed of lathe chuck, friction time, burn-off length, and the joint is examined by a tensile test to check its strength. Taguchi's orthogonal array was used to design the experiment and at the end, the ANOVA test is carried out for the optimization of process parameters.
Keywords: Friction Welding, Joining of Dissimilar Materials, Aluminium 6061, Mild Steel, ANOVA

I. INTRODUCTION

Friction welding is a solid-state joining process that produces a metallic bond due to the effect of the rubbing action of a rotating component over a stationary component is taking place. Friction welding can be used to weld similar and dissimilar materials. Thus, mechanical friction is developed between those components and they started heating so that, the interface temperature has increased. During this, firstly the rotating energy was converted into frictional energy and then further into heat energy. Both components go into a plastic state where a high mechanical force is applied to that component to form an upset. The mechanical force is a lateral upset force that is used to plastically displace and fuse the materials. When sufficient heat energy is developed, the rotating component is stopped and mechanical force applied, to forge the component together and form a solid-state metallic bond. In the traditional sense, friction welding is a forging process because technically no melting of the component has occurred here. The friction welding process can be performed without the use of filler material, gas, tool, and external medium for heat generation; it uses friction, rotational speed, and upset force for effective joining. Thus, it is an economical welding process as compare to arc and butt welding. It is a solid-state process; the two dissimilar materials having different melting temperatures can be weld by this process thus welding is independent of melting point and hence it avoids solidification defects like porosity, segregation

II. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for friction welding. The conventional lathe machine is used for such welding by modifying tailstock arrangement with drill chuck.

Fig.1 Experiment Set-Up

The mild steel was held in a lathe chuck whereas aluminium 6061 was in a drill chuck. The drill chuck only moved longitudinally according to the upset force which was given manually through the tailstock wheel. The lathe was worked with three rotational speeds i.e. at 686,816 and 1000 rpm.

Fig. 2 Conventional Lathe Machine

III. EXPERIMENTATION

Standard specimen ASTM E-8 dimension is used for the specimen of friction welding joint. This standard represents the tensile test on a metallic component. The half portion of the specimen is made up of aluminium 6061 and the other half is mild steel. They are both joined by friction welding on the lathe.

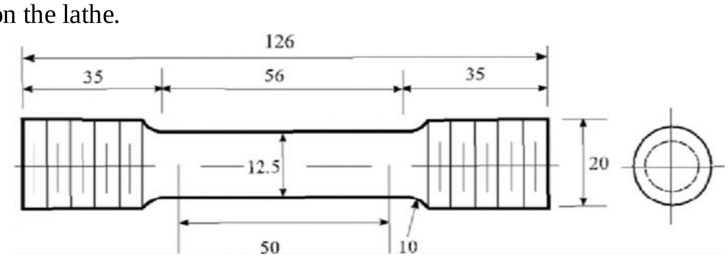

Fig. 3 ASTM E8 standard specimen with dimension in mm

The rods of aluminium 6061 and mild steel of diameter 25 mm and length 800 mm were cut over the power saw into 9 equal parts. Then some portion of material from the aluminum 6061 was removed for holding arrangement in drill chuck. Further, the hard material mild steel was held in a lathe chuck and rotates at a particular input rpm for a particular input time, and then aluminium 6061 was forced manually towards the mild steel. The friction and simultaneously heat were generated while applying force. Both materials softened and go into plastic deformation. As the troublesome happened in rotation of the mild steel then the friction welding joint of aluminium 6061 and mild steel was completed. The rotation of drill chuck, welding time, and burn-off length are used as input. Thus 9 experiments were performed with these combinations of input.

Fig. 4 Aluminium

Fig. 5 Mild Steel

The heat generation between the mild steel and aluminium due to friction is shown in fig 6. As the melting point and hardness aluminium is minimum than mild steel, high plastic deformation of aluminium is formed which is shown in fig 7.

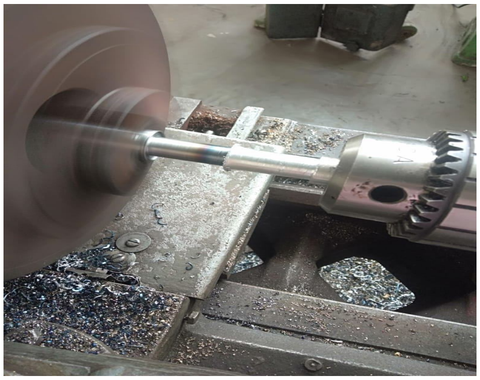

Fig. 6 Heat Generation in Weld Joint Plastic

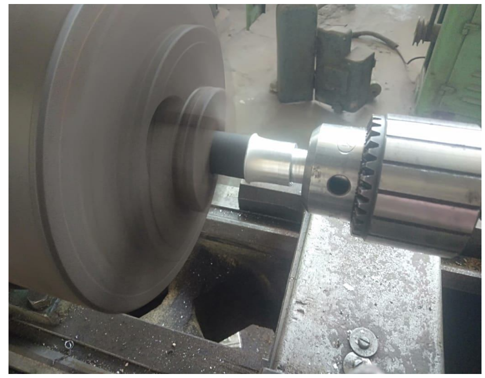

Fig. 7 Deformation of Aluminium

By using the combinations of input process parameters, the orthogonal array is formed for DOE and according to this, all 9 experiments are carried out.

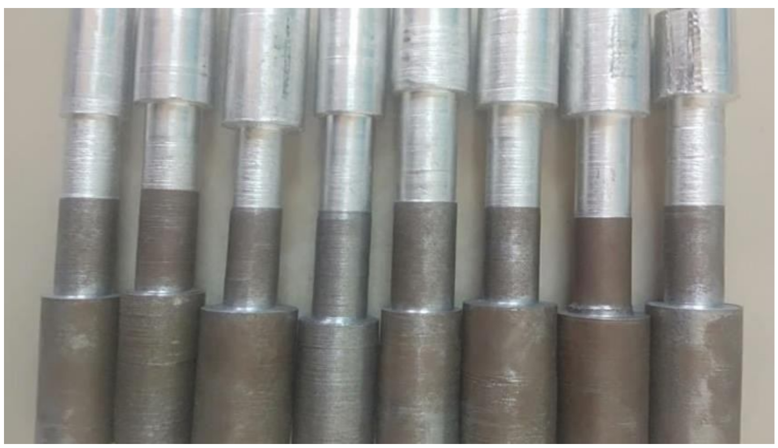

Fig. 8 Friction Welded Samples

IV. PROCESS PARAMETER

The process parameters with their different level which is shown in table 1 are used for this research work. By using the L9 orthogonal array and various combinations of input, the friction welding joint of aluminium 6061 and mild steel was formed on the lathe. The *rotational speed* is the spindle speed of the lathe and it is measured in revolution per minute. The *welding time* or friction time is the time for which aluminum 6061 and mild steel are forcefully in contact with each other and joining is completed at end of time. The *burn-off length* is the amount length of material reduced in the welding process.

Table 1 Process Parameters with Different Level

Sr no	Level of parameter		
	Rotational Speed (rpm)	Welding time (s)	Burn-off length (mm)
1	686	60	1
2	816	120	2
3	1000	180	3

V. RESPONSE PARAMETER

The response parameter is nothing but the output of the experiment. This output depends on the input and its combination. The Two response parameters are used in research work i.e. Ultimate load and ultimate tensile strength. The *ultimate load* is the maximum load-carrying of the weld joint while *ultimate tensile strength* is the maximum stress induced in the joint before fracture. Both responses should be maximum is a requirement of this research work. The maximum strength of the weld joint is allowed to use of similar or dissimilar joints of material in different application areas.

VI. TENSILE TEST

The tensile test on friction welded joint was performed on the Universal testing machine of 400 KN capacity. The maximum load and maximum tensile strength that the welded sample can carry before fractured are shown in the following table 2. The maximum tensile strength and maximum load are obtained for experiment 9 whereas the minimum values are obtained for experiment 1 respectively.

a) UTM

b) Workpiece Position

c) Loading and Testing

Fig. 9 Tensile Testing of Welded Joint on UTM 400 kN

The above figure shows that the UTM machine (a), the welded sample is held between heads or jaw of UTM (b) and then the tensile load is applied (c). The sample is weak at the joint hence it breaks at that joint and ultimate tensile load is obtained. Further, with help of the load-cross-sectional area relationship, ultimate tensile strength is calculated.

Table 2 Tensile Test Results

Sr. No.	Rotational Speed (Rpm)	Welding Time (S)	Burn- off Length (mm)	Ultimate Load (kN)	Ultimate Tensile Strength (MPA)
1	686	60	3	3.12	25.42
2	686	120	2	6.23	50.76
3	686	180	1	8.64	59.89
4	816	60	2	7.35	70.41
5	816	120	1	9.45	72.68
6	816	180	3	8.92	77.00
7	1000	60	1	10.08	82.14
8	1000	120	3	10.72	87.35
9	1000	180	2	11.92	97.13

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VII. ANALYSIS

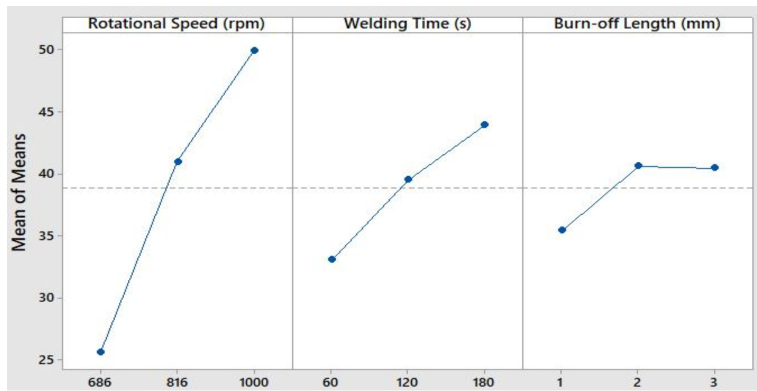
The analysis of the process parameters and responses of this experiment was done with the use of MINITAB-18 software. In this analysis, the Taguchi method was used to investigate how given input parameters affect the output, and also it is used for designing the experiment that contains different input combinations i.e. orthogonal array. Further mean plots, regression equation, response table, and at end ANOVA was also used for analysis.

A. Main Effect Plots and Response tables

The main effect plot for means is shown in above Graph-1. It examines the difference between the mean of the level of parameters and creates the effect when inputs differently affect the output. According to the graph, it is seen that increase in rotational speed and welding time will lead toward an increase in the responses whereas in the case of burn-off length up to a 2 mm response.

Table 3 Response Table for Means

Level	Rotational Speed (rpm)	Welding Time (s)	Burn-off Length (mm)
1	25.68	33.09	35.42
2	40.97	39.53	40.63
3	49.89	43.92	40.48
Delta	24.21	10.83	5.21
Rank	1	2	3



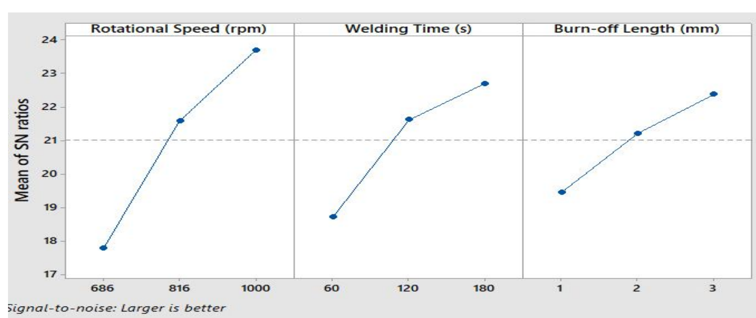
Graph 1 Main Effect Plot for Means

Above table 3 shows the response for mean. It is noted that rotational speed has the maximum mean difference value of 24.21 whereas burn-off length has a minimum value of 5.21, thus rotational speed creates more impact on the response as compared to welding speed and burn-off length and due to this, it has a steeper inclined line. After the burn-off length of 2 mm, the line tends to become horizontal and thus, very low or no effect produce on responses.

The SN ratio is the measure of robustness and it is used for finding those control factors (single) which reducing flexibility and variability in experiments by controlling the effect of uncontrol factors (noise). The control factor is process parameters while uncontrol factors are responses. The maximum SN ratios for each parameter show the optimum input parameter which gives the optimum result. The corresponding value of the parameter's level is taken as an optimum input parameter.

Table 4 Response Table for SN Ratios

Level	Rotational Speed (rpm)	Welding Time (s)	Burn-off Length (mm)
1	17.77	18.71	19.45
2	21.56	21.61	21.20
3	23.68	22.69	22.37
Delta	5.91	3.98	2.92
Rank	1	2	3



Graph 2 Main Effect Plot for SN Ratios

The main effect plots for SN ratios are quite similar to the plots for means, From table 4, it is shown that the maximum SN ratios are 23.68, 22.69, and 22.37 for rotational speed, welding time, and burn-off length respectively, that is obtained at level 3 of all process parameter. Thus, the rotational speed of 1000 rpm, welding time of 180 s, and burn-off length of 3 mm are the factors responsible for reducing the variability.

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B Regression Equation

The regression equation was also generated which forecasted the results based on input factor.

1) Regression Equation for the ultimate load (kN)

Ultimate load(kN)^2 = 78.30- 37.23 Rotational speed(rpm)_686- 4.00 Rotational speed(rpm)_816
+ 41.24 Rotational speed(rpm)_1000- 23.18 Welding Time(s)_60
+ 2.71 Welding Time(s)_120+20.47 Welding Time(s)_180+10.22 Burnoff length(mm)_1
+ 0.01 Burn-off length(mm)_2 - 10.23 Burn-off length(mm)_3

2) Regression Equation for Ultimate Tensile Strength (MPa)

Ultimate Tensile Strength (MPa)^2 = 5198.912929 Rotational speed(rpm)_686+ 191 Rotational speed(rpm)_816
+32738 Rotational speed(rpm)_1000-1082 Welding Time(s)_60
-36 Welding Time(s)_120+ 1118 Welding Time(s)_180+ 7 Burn-off lengths(mm)_1
+ 457 Burn-off lengths (mm)_2- 464 Burn-off length(mm)_3

C ANOVA

Analysis of Variance (ANOVA) was used to find out the importance of input factors and gives information about the quantitative contribution of process parameters with the comparison of the output response means at the different levels. ANOVA is carried out to evaluate the contribution and significance of process parameters on joint strength and load by using the ultimate load and ultimate tensile strength as the response parameters (larger is better)

1) *ANOVA for Ultimate Load*: The ANOVA result of inputs for Ultimate load is shown in the following table. The P-value is lower than the significance level of 0.05 for rotational speed and welding time whereas the p-value is greater than 0.05 for burn-off length. Thus, there is a difference between the means of inputs at a different level.

Table 5 Analysis of Variance for Ultimate Load

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Rotational speed (rpm)	2	9308.8	71.95%	9308.8	4654.38	82.94	0.012
Welding Time (S)	2	2890.6	22.34%	2890.6	1445.29	25.76	0.037
Burn-off length (mm)	2	627.1	4.85%	627.1	313.54	5.59	0.152
Error	2	112.2	0.87%	112.2	56.12		
Total	8	1238.7	100.00%				

From pie chart 1, it observed that the rotational speed parameter contributing more to the ultimate load as compare other two parameters.

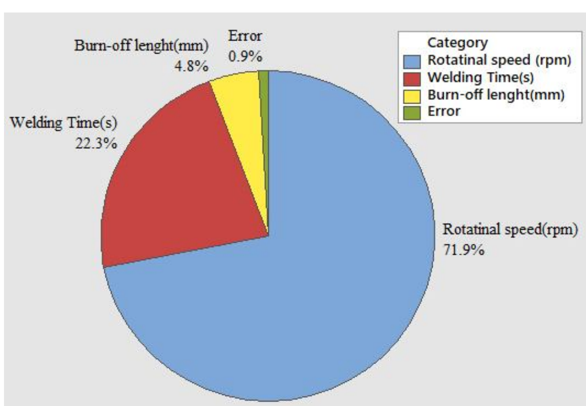

Chart 1 Percentage Contribution of Process Parameters Ultimate Load (kN).

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2) *ANOVA for Ultimate Tensile Strength*: The ANOVA result of inputs process parameters for Ultimate tensile strength is shown in the following table. The P-value is lower than the significance level of 0.05 for rotational speed and welding time whereas the p-value is greater than 0.05 for burn-off length. Thus, there is a difference between the means of at a different level and it produces the effect of ultimate tensile strength.

Table 5 Analysis of Variance for Ultimate Tensile Strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Rotational speed (rpm)	2	48339948	84.74%	48339948	24169974	286.10	0.003
Welding Time (s)	2	7264304	12.73%	7264304	3632152	42.99	0.023
Burn-off length (mm)	2	1272723	2.23%	1272723	636361	7.53	0.117
Error	2	168962	0.30%	168962	84481		
Total	8	57045936	100.00%				

Similarly, as in the case of ultimate load, the rotational speed parameter contributing more to the ultimate tensile strength as compare other two parameters which is shown in chart 2.

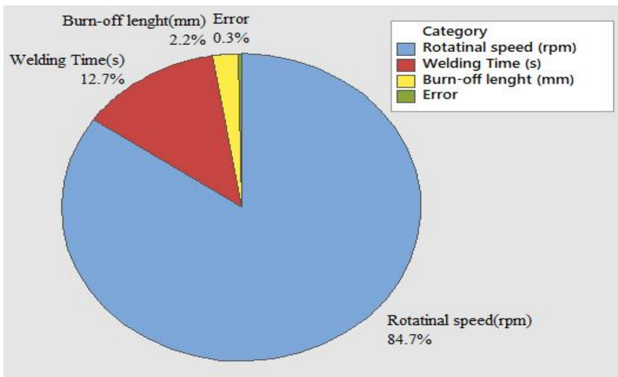

Chart 2 Percentage Contribution of Process Parameters for Ultimate tensile strength (MPa)

VIII. RESULT

The results of this research work are formed based on the tensile test, Taguchi's analysis, and ANOVA.

A. All the weld joint samples of dissimilar material i.e. aluminium and mild steel were in good condition.

B. It is shown from the result, that maximum load-carrying capacity of 11.92 kN and maximum tensile strength of 97.13 MPa of weld joint is obtained for experiment 9 when welding was done at the rotational speed of 1000 rpm for welding time of 180 s and burn-off length of 2 mm whereas minimum values were obtained at the rotational speed of 686 rpm for welding tine of 60 s and burn- off length 3 mm respectively.

Table 6 Maximum and minimum responses

Experiment	Rotating speed(rpm)	Welding time (mm/min)	Burn-off Time (mm)	Ultimate Load (kN)	Ultimate tensile strength (MPa)
9	1000	180	2	$P_{max} = 11.92$	$\sigma_{max} = 97.13$
1	686	60	3	$P_{min} = 3.12$	$\sigma_{min} = 25.42$

C. The main effect plot for means and SN ratio shows that all the input process parameters i.e. rotational speed and welding time and burn-off length differentially affect the output response except the burn-off level line for the SN plot.

D. Both response tables show that rotational speed plays a significant and very important key role in the friction welding joint as compare to the welding time and burn off the length. From the response table of SN ratio, it shows that the rotational speed of 1000 rpm, welding time of 120 s, and burn-off length of 3 mm are the factors responsible for reducing the variability.

E. ANOVA results showed that rotational speed and welding time are the significant process parameters for both responses and both parameters have a p-value lower than the significance level of 0.05. and burn-off length is an insignificant process parameter having a p-value of more than the significance level of 0.05 for both responses. The percentage contribution of all process parameter to each response are shown in the following table

Table 7 ANOVA Result for Responses

Responses	Parameter	P-value	Contribution	Remark
Ultimate load	Rotational speed	0.012	84.74%	Significant
	Welding time	0.037	12.73%	Significant
	Burn-off length	0.152	2.23%	Insignificant
Ultimate tensile strength	Rotational speed	0.003	71.95%	Significant
	Welding time	0.023	22.34%	Significant
	Burn-off length	0.117	4.85%	Insignificant

IX. CONCLUSION

In this research work, the dissimilar welding joint of aluminium 6061 and mild steel has been completed successfully. The welding joints obtained in this work are in good condition and exhibit good tensile strength. The rotational speed is the most significant, contributor and important process parameter to both responses. Maximum tool rotation speed results in maximum heat input to the joint through the friction and also welding or friction time should be more for heat generation at the contact.

X. ACKNOWLEDGEMENT

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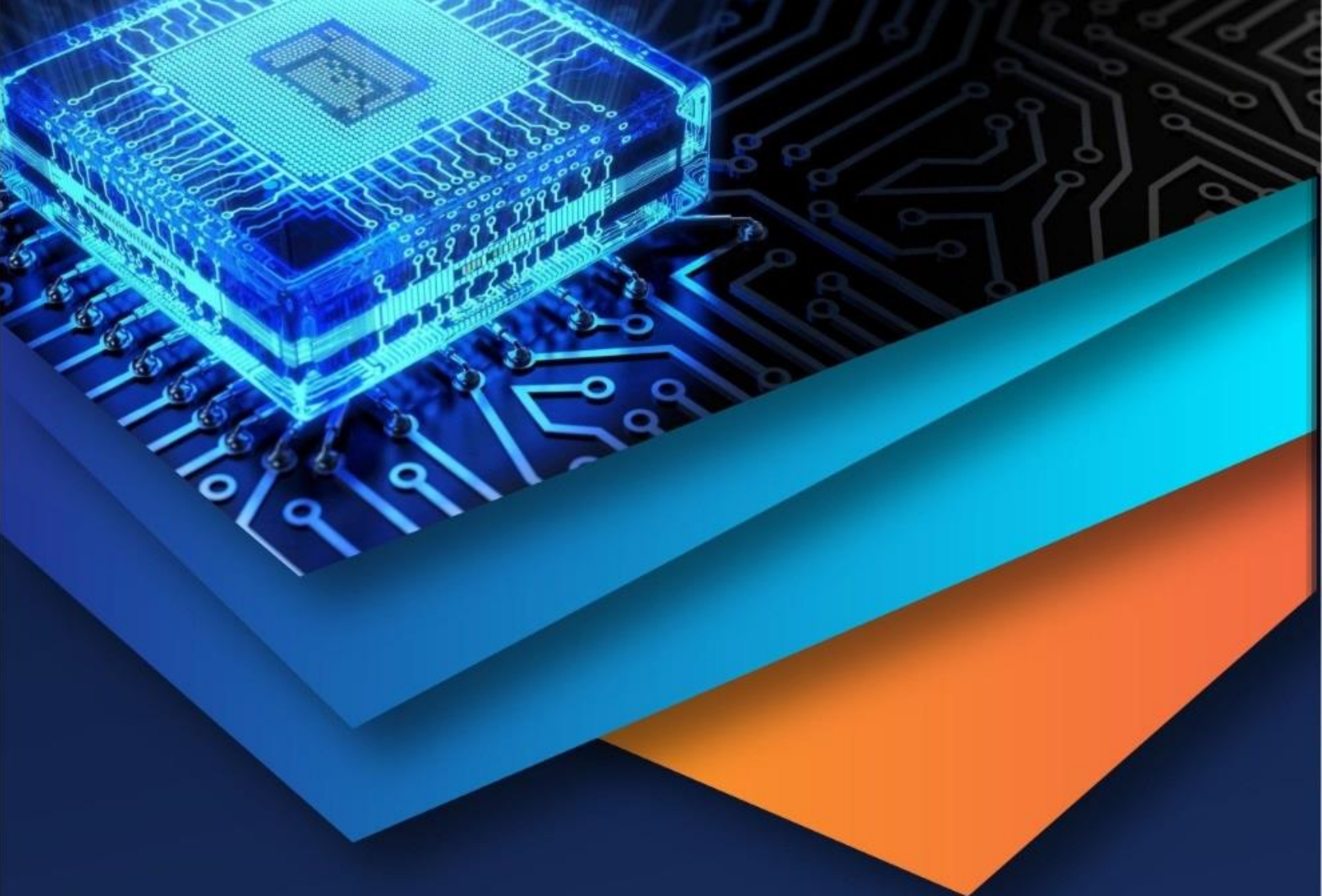

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