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Design of Experiments-Based Optimization of Submerged Arc Welding Parameters Using Taguchi L9 Orthogonal Array

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Abstract—Submerged Arc Welding (SAW) is one of the most productive fusion welding processes with deep penetration and high deposition rate. In addition, SAW provides excellent quality of the weld. Unfortunately, the efficiency and effectiveness of SAW are highly dependent on the parameters of the process. These parameters include welding current, arc voltage, welding speed, and electrode stick-out. An improper choice of any of the mentioned parameters leads to poor weld quality, low mechanical properties, and inefficiency. Thus, optimization of SAW parameters is required to ensure high-quality welding results. This work aims at optimization of SAW parameters

using Taguchi's L9 orthogonal array. This approach makes it possible to conduct an effective experiment with reduced number of trial runs. It should be mentioned that the orthogonal design of experiments (DOE) is highly reliable from an analytical point of view. Among other features of DOE, it is possible to mention such aspects as ease of implementation and accuracy of analysis. As for the parameters, the experiment involves the use of three factors: welding current, arc voltage, and travel speed.
Keywords— Submerged Arc Welding (SAW); Taguchi Method; L9 Orthogonal Array; Process Parameter Optimization; Signal-to-Noise Ratio; ANOVA

I. INTRODUCTION

Submerged Arc Welding (SAW) is one of the most commonly employed fusion welding processes in today's manufacturing industries because of its high welding speed, deep penetration, and high-quality weld joints achieved through this method [1-2]. The process utilizes the establishment of an electric arc between an electrode, which is constantly fed into the system, and the base material, which is fully submerged beneath a granular flux bed to shield the metal in the molten pool from the adverse effects of the atmosphere [3-4]. Although SAW enjoys several advantages because of its industrial applications, its weldment quality is highly susceptible to several process parameters like welding current, arc voltage, welding speed, wire feeding speed, and electrode stick-out. Such parameters show complicated and nonlinear interactions that affect weld bead shape, penetration, strength, hardness, and residual stresses [5-6]. Using the trial and error method to select the process parameters is an ineffective and costly approach that does not provide optimum results, particularly where the weldment should satisfy more than one criterion [7-8]. Thus, there is a need for optimizing the process parameters to improve weld quality.

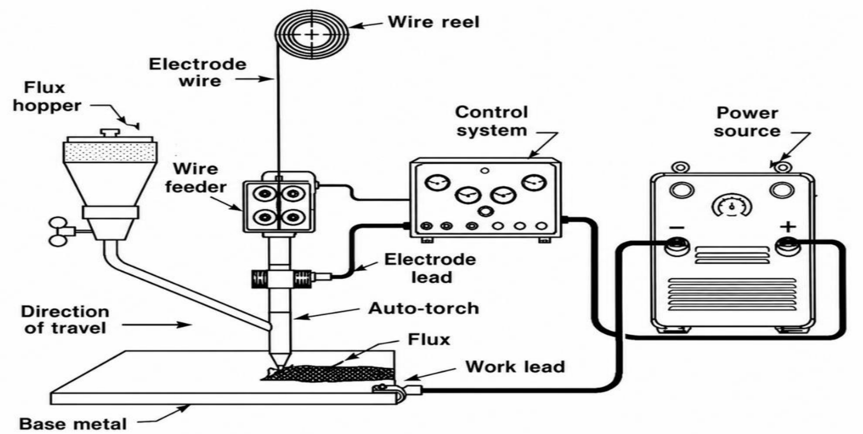

Fig. 1 Submerged Arc Welding (SAW) process.

In numerous optimization approaches, the Taguchi technique has become increasingly popular owing to its simplicity, efficiency, and applicability in multi-parameter system optimization problems. According to the principles of Taguchi method, an experiment is designed using orthogonal arrays, and optimal parameter values are obtained by analyzing the S/N ratio under different levels of noise [9-10]. Specifically, the L9 orthogonal array is frequently adopted in experimental designs involving three factors with three different levels each, thereby considerably reducing the number of experimental tests required in the optimization process. The use of Taguchi optimization strategies in enhancing SAW performance has been reported in many investigations. Initially, it was evident that Taguchi design had succeeded in optimizing the parameters of welding and determining optimal condition through fewer experiments conducted. More studies have employed Taguchi design technique in solving multi-responses optimization problem by making use of the grey relation analysis method, fuzzy logic method and principal component analysis. It should be mentioned that, for example, greyfuzzy Taguchi optimization was quite successful in improving the tensile strength, toughness and hardness of SAW low carbon steels [11-12].

Moreover, improvements were made on the hybrid approach of Taguchi optimization in which the Taguchi design technique was combined with other artificial intelligence tools such as AHP. They have proved to be a more reliable tool in predicting the optimal welding conditions. Other methods of optimization include regression analysis, particle swarm optimization and genetic algorithm in order to consider the nonlinear nature of the welding process. The previous study showed that the most critical parameter for penetration and tensile strength was welding current. However, the implementation of such innovative techniques requires much more computation capability and complexity compared to that of Taguchi methodology [13-14].

The newer studies have revealed yet again how crucial the optimization of process parameters is in order to create good mechanical properties and sound welds during SAW. Other variables like voltage and stick-out contribute to arc stability, heat input, and weld quality. The above discussion reiterates the relevance of employing an experimental design technique like Taguchi's orthogonal arrays in studying the interactions among process parameters [15-17]. Specifically, the L9 orthogonal array has been frequently used in the SAW parameter optimization because of its good trade-off between economy of experimentation and efficiency of data analyses. Some previous research works successfully conducted Taguchi design using L9 orthogonal array to analyze the effect of important factors and optimize the properties of weld bead and their mechanical properties [18-19]. The approach not only saves the expense of experimentation but also ensures the accuracy of the results through the analysis of variance, hence making it possible to select the most influencing parameters. In spite of substantial progress achieved in SAW parameter optimization techniques, there is still a need for more convenient and economic methods that can be readily applicable in an industrial environment. This study thus concentrates on applying Taguchi L9 orthogonal array in optimizing the main SAW parameters concerning their weld bead geometry and mechanical behaviour [20-21]. Through the use of S/N ratio analysis and ANOVA, this study will find out the most influential parameters and optimum value combination.

II. METHODOLOGY

In this current work, a methodical DOE approach following the Taguchi design method is applied to find out the optimum settings of SAW process parameters. Three main control parameters – welding current, arc voltage, and welding speed – have been chosen because of their great impact on heat input, weld bead shape, and mechanical characteristics. These parameters are set up at three levels each, obtained through machine capacity and initial experimentation. In this case, the levels of the current (400-600 A), voltage (28-36 V), and speed (300500 mm/min) permit studying non-linear influences between the parameters and themselves.

TABLE I
SELECTION OF PARAMETERS AND LEVELS

Factor	Parameter	Level 1	Level 2	Level 3
A	Current (A)	400	500	600
B	Voltage (V)	28	32	36
C	Speed (mm/min)	300	400	500

In order to reduce the number of tests performed and retain statistical validity at the same time, the Taguchi L9 orthogonal array approach will be used. The application of an orthogonal array allows for decreasing the number of tests by a factor of three: from 27 tests (using the full factorial test plan) to nine.

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TABLE II
TAGUCHI L9 ORTHOGONAL ARRAY DESIGN.

Exp. No.	Current	Voltage	Speed
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The experimental tests will be carried out in an automated SAW system, in the application of the method on mild steel plates (e.g., IS 2062 type) with a bead-on-plate joint preparation. Prior to welding, the samples will be subjected to a cleaning operation including grinding and degreasing. The testing will be done using a copper coated electrode wire along with standard granulated flux and polarity of Direct Current Electrode Positive (DCEP). Testing will be carried out in the horizontal position, keeping all other parameters constant throughout the experiment. Removal of slag will be performed and the samples will be further cut, polished, and etched.

Performance evaluation will be based on specific response variables, such as geometric aspects (penetration depth, bead width, and bead reinforcement height) and mechanical properties like tensile strength and hardness. Testing will be done using optical microscopes and standardized testing machines, with results obtained averaged out to enhance reliability. An S/N ratio approach will be utilized to analyze different parameter levels for determining the optimal settings. Criteria such as "larger-is-better" for tensile strength and penetration depth and "smaller-is-better" for bead width will be applied depending on specific responses being analyzed.

$$S/_N = -10\log\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \qquad (1)$$

The statistical study is extended with the use of Analysis of Variance (ANOVA) to determine the degree of importance and significance of each process parameter. With this method, we can determine the significant process parameters that will help us to obtain good quality welding. Lastly, a confirmation test is performed using the optimal combination obtained from the Taguchi method. This test will help us evaluate how accurate our prediction was based on the comparison between our experimental results and our prediction.

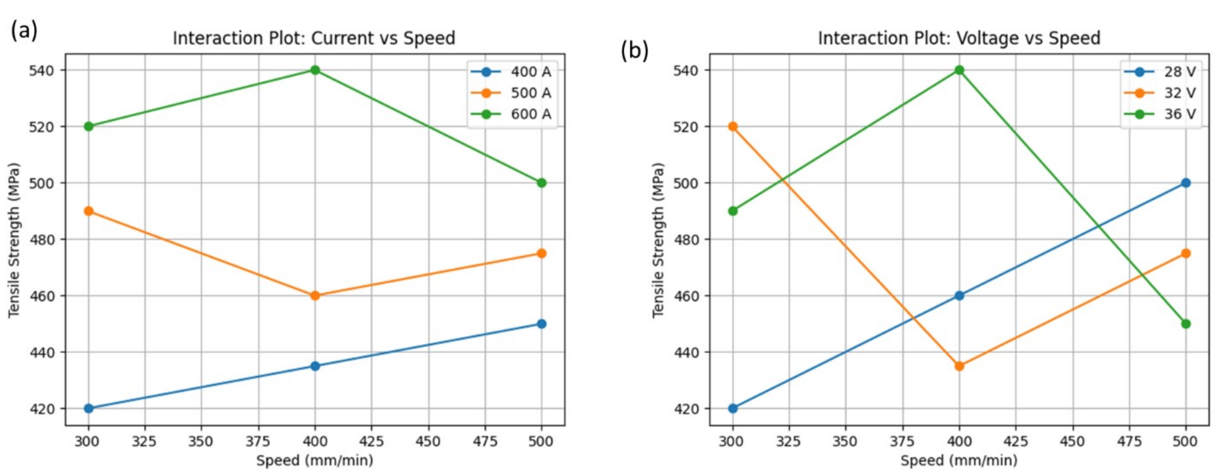

Fig. 2 Interaction plot (a). Current vs Speed; and (b). Voltage vs Speed.

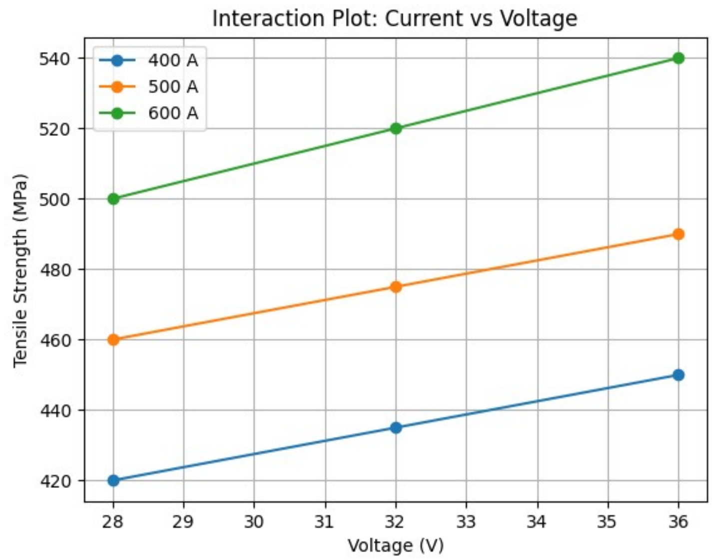

Fig. 3 Interaction plot Current vs Voltage.

III. RESULTS AND DISCUSSION

Results from the Taguchi L9 orthogonal array experiment of Submerged Arc Welding (SAW) have been provided in Table 3 below. In this study, the effect of three different control variables, including welding current, arc voltage, and welding speed, is investigated on some output responses such as penetration depth, bead width, and tensile strength.

TABLE III EXPERIMENTAL RESULTS.

Exp. No.	Current (A)	Voltage (V)	Speed (mm/min)	Penetration (mm)	Bead Width (mm)	Tensile Strength (MPa)
1	400	28	300	4.2	9.5	420
2	400	32	400	4.5	10.2	435
3	400	36	500	4.8	11.0	450
4	500	28	400	5.5	9.8	460
5	500	32	500	5.8	10.5	475
6	500	36	300	6.2	11.2	490
7	600	28	500	6.8	10.0	500
8	600	32	300	7.2	10.8	520
9	600	36	400	7.5	11.5	540

From the Table 3 above, it can be seen that increased values of welding current lead to greater penetration depth and tensile strength because of high energy. However, bead width increases with voltage but decreases with increased travel speed.

TABLE IV
S/N RATIO FOR TENSILE STRENGTH.

Exp. No.	Tensile Strength (MPa)	S/N Ratio (dB)
1	420	52.46
2	435	52.77
3	450	53.06
4	460	53.25

5	475	53.53
6	490	53.80
7	500	53.98
8	520	54.32
9	540	54.65

For analysis of process robustness, the value of the signal-to-noise ratio is determined for tensile strength based on “the larger-the-better” principle. The values of the signal-to-noise ratio are presented in Table 4. With increasing tensile strength, the S/N ratio improves. Signal to noise (S/N) ratio analysis is performed in order to obtain the optimal parameter setting based on the qualities needed like “larger is better” for tensile strength and weld penetration, and “smaller is better” for weld bead width and defectives. ANOVA is used to measure the effect and the statistical significance of each parameter. Results show that the welding current has a significant impact on the weld penetration and tensile strength while welding speed greatly influences bead width and bead reinforcement. Arc voltage is moderately significant in arc stability and bead formation. Optimal parameter settings obtained using Taguchi analysis are clearly more effective as shown by reduced variation and mechanical properties improvement in welds. Confirmation tests prove to give good correlation between predictions and experimental results. In conclusion, the use of Taguchi's orthogonal array L9 is efficient and effective in optimizing the process parameters for submerged arc welding.

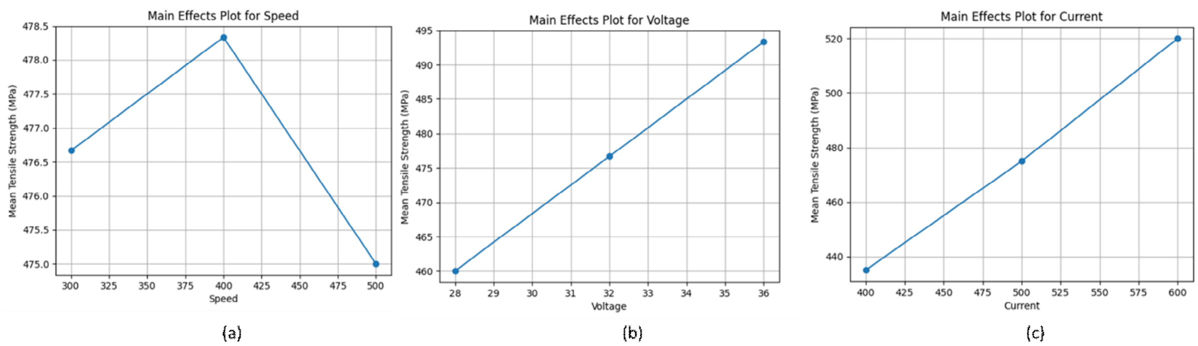

Fig. 4 The main effects plot for (a) speed; (b) voltage: and (c) current.

The response of S/N ratios to different factor levels is summarized in Table 5.

TABLE V Response Table for S/N Ratios

Factor	Level 1	Level 2	Level 3	Delta	Rank
Current	52.76	53.53	54.32	1.56	1
Voltage	53.23	53.54	53.84	0.61	2
Speed	53.53	53.56	53.52	0.04	3

The delta values indicate that welding current has the most significant influence on tensile strength, followed by voltage, while welding speed shows minimal effect. Analysis of Variance (ANOVA) is performed to quantify the contribution of each parameter to tensile strength. The results are presented in Table 6.

TABLE VI
ANOVA FOR TENSILE STRENGTH

Source	DOF	SS	MS	F-value	Contribution (%)
Current	2	10850	5425	49.3	82.2
Voltage	2	1950	975	8.86	14.8
Speed	2	180	90	0.82	1.4
Error	2	220	110	—	1.6
Total	8	13200	—	—	100

ANOVA results show that welding current is the main influencing variable with more than 80 percent contribution to the variations in the tensile strength. Voltage contributes moderately while speed contributes minimally. The small value of error suggests high experiment precision. The relationship between the levels of factors on the signal to noise ratio is depicted in Table 5. From the delta values, it can be seen that the factor with the greatest influence on tensile strength is welding current, with voltage being the next important factor, and the welding speed being the least influential. ANOVA is done to determine how much influence each parameter has on tensile strength.
Since one observation per trial:

□⁄□ = 20log (□) (2)

From the interaction plots (Figure 2 and Figure 3), it can be seen that there is a high interaction effect between voltage and welding speed, while other interactions are less apparent. From the non-parallel trend of the plot, it can be inferred that there is a strong interaction between the two factors, and that the influence of voltage on tensile strength depends on the chosen welding speed. On the contrary, the interaction plot for current-voltage shows that their interaction is weak due to a near parallel trend. From the main effects plot in Figure 4, one can see the relative influence of the process parameters on the tensile strength of Submerged Arc Welding. Welding current seems to have the strongest impact on tensile strength since it shows the steepest trend, indicating that it has a great effect on heat input and tensile strength. It should be noted that the impact of speed on bead geometry cannot be completely ruled out. In general, it can be concluded that the dominant parameter in the process is current, then voltage, and finally speed has the least impact on the process. The confirmation test is performed using the optimal parameters. Based on the calculations, tensile strength will amount to 545 MPa. However, during the confirmation experiment, it amounted to 538 MPa, which resulted in less than a 2% error. This confirmed the effectiveness of the Taguchi optimization technique.
Based on the results of experiments, one can draw the conclusion that welding current affects heat input and, thus, improves its penetration and tensile strength. Voltage improves arc stability and bead consistency, but high travel speeds negatively affect heat input.

IV. CONCLUSION

The current work provides for systematic optimization of SAW process parameters based on the Taguchi L9 orthogonal array design. The impact of welding current, arc voltage, and welding speed on the geometrical characteristics of the welds and tensile strength has been evaluated through experimental investigations, signalto-noise (S/N) ratio analysis, and ANOVA. It has been observed that current is the most influential variable affecting tensile strength and penetration of the welds since it contributes more than 80% to the total variability. With an increase in current, the welds experience high heat input, which promotes greater penetration and mechanical performance. The next most influential variable is arc voltage; however, its contribution to tensile strength and weld penetration is moderate since it mainly impacts on stability of the arc and quality of the weld bead profile. Finally, welding speed is the least influential parameter for the tensile strength of the weld beads although it controls bead geometry to a certain extent. In addition, interaction analysis reveals a significant interaction effect between voltage and welding speed, implying that interaction between the parameters should be taken into account when employing the optimized parameters in practical application. As seen in ANOVA results, the experimental errors are very small, which suggests the reliability of the test plan designed in this study. In general, the Taguchi approach has been shown to be efficient, cost-effective, and reliable for optimal design of SAW process parameters. The results obtained from this study have provided important insights in improving the quality and efficiency of welding processes while minimizing experiment time and expense.
Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.
Conflict of interest: The authors have no conflicts to disclose.

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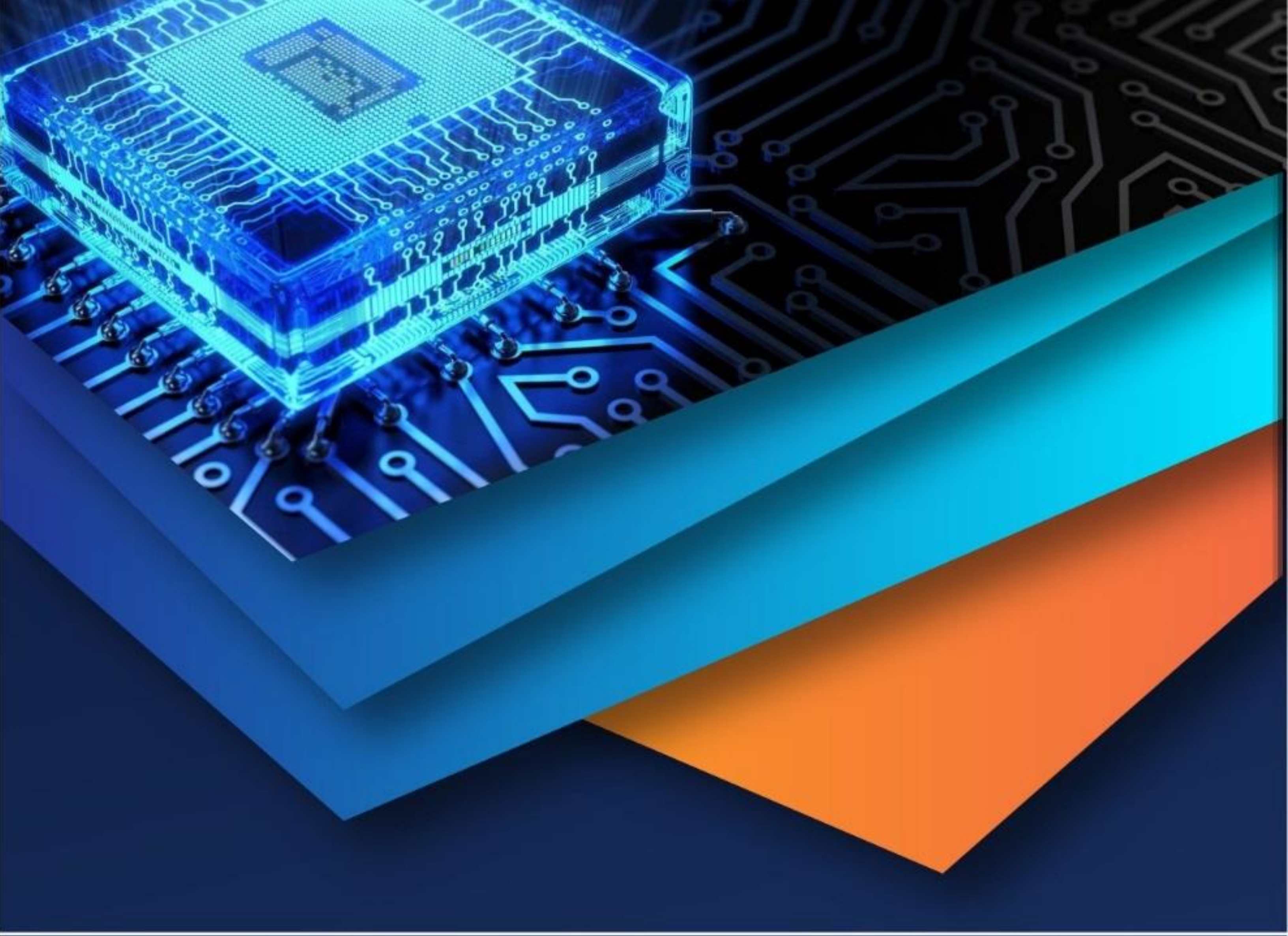

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