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Structural and Thermal Analysis of Engine Cylinder Fins by Varying Geometries and Materials

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Abstract: Efficient cooling of air-cooled internal combustion engine cylinders is essential to maintain safe operating temperatures, reduce thermal stresses, and enhance engine durability. In the present study, a comparative numerical investigation of the structural and thermal performance of engine cylinder fins with varying geometries and materials is carried out. Three fin configurations—circular, triangular, and sinusoidal—are modelled and analysed using ANSYS Workbench. Aluminium 6061 and Aluminium 2024 alloys are considered as fin materials due to their widespread application in automotive engines. Static structural analysis is performed to evaluate deformation, von Mises stress, and factor of safety under identical loading conditions. Steady-state thermal analysis is conducted by applying heat flux at the inner cylinder wall and convective heat transfer on the outer fin surfaces. The results indicate that circular fins provide superior structural integrity with minimal deformation and higher safety factors. Sinusoidal fins demonstrate a balanced performance in terms of both thermal efficiency and structural strength. The study concludes that a trade-off between cooling effectiveness and mechanical reliability is necessary, and sinusoidal fins made of Aluminium 2024 offer an optimal compromise for air-cooled engine applications.
Keywords: Air-cooled engine, Cooling fins, Heat transfer, Structural analysis, Thermal analysis, ANSYS.

I. INTRODUCTION

Air-cooled internal combustion engines are widely used in two-wheelers due to their simplicity, lower manufacturing cost, and reduced maintenance requirements. A significant portion of the heat generated during combustion is absorbed by the engine cylinder, and inadequate heat removal may lead to excessive thermal stresses, reduced lubrication effectiveness, and shortened engine life. Cooling fins mounted on the outer surface of the cylinder enhance heat dissipation by increasing the exposed surface area and improving convective heat transfer.

The performance of cooling fins strongly depends on their geometry, material properties, and interaction with airflow. Conventional fin designs may not always provide optimal thermal performance under practical operating conditions. Recent studies have shown that non-conventional fin geometries such as circular, tapered, and wavy profiles can improve heat transfer characteristics when compared to traditional rectangular fins. Additionally, aluminium alloys such as Al-6061 and Al-2024 are commonly used due to their favourable thermal conductivity, strength-to-weight ratio, and corrosion resistance.

Although several investigations have focused either on thermal or structural aspects of fin performance, limited studies are available that simultaneously compare multiple fin geometries and materials under identical boundary conditions. The present work addresses this gap by performing a combined structural and thermal analysis of circular, triangular, and sinusoidal fins using two aluminium alloys.

II. LITERATURE REVIEW

Cooling fins play a crucial role in maintaining acceptable operating temperatures in air-cooled internal combustion engines. Several researchers have investigated the influence of fin geometry, material selection, and numerical simulation techniques to enhance heat dissipation from engine cylinders.

Early studies on engine cooling fins focused on conventional rectangular and annular fin geometries. Rajput [1] emphasized that increasing fin surface area significantly improves convective heat transfer in air-cooled engines, although excessive fin thickness may lead to higher weight without proportional thermal benefits. Gupta [2] reported that aluminium alloys are preferred fin materials due to their high thermal conductivity and low density.

Material selection has also been shown to influence fin performance. Rajat Yadav et al. [5] compared Aluminium 2024 and Aluminium 6061 fins under identical conditions and concluded that Aluminium 6061 provides better corrosion resistance, while Aluminium 2024 offers superior mechanical strength. However, their work primarily focused on thermal behaviour and did not include detailed structural comparison. More recent studies have combined structural and thermal analyses to evaluate fin effectiveness. Kannadhasan et al. [6] validated CFD and experimental results for various fin geometries and reported that wavy and curved fin profiles enhance convective heat transfer by inducing airflow turbulence. Their findings suggest that sinusoidal fin shapes can improve cooling efficiency while maintaining acceptable stress levels.

III. MATERIALS AND METHODOLOGY

A. Modelling and Material Selection

Three fin geometries—circular, triangular, and sinusoidal—are designed around an identical base engine cylinder to ensure fair comparison. The dimensions of the cylinder and fins are kept constant across all configurations. Aluminium 6061 and Aluminium 2024 are selected as fin materials due to their common usage in air-cooled engine applications.

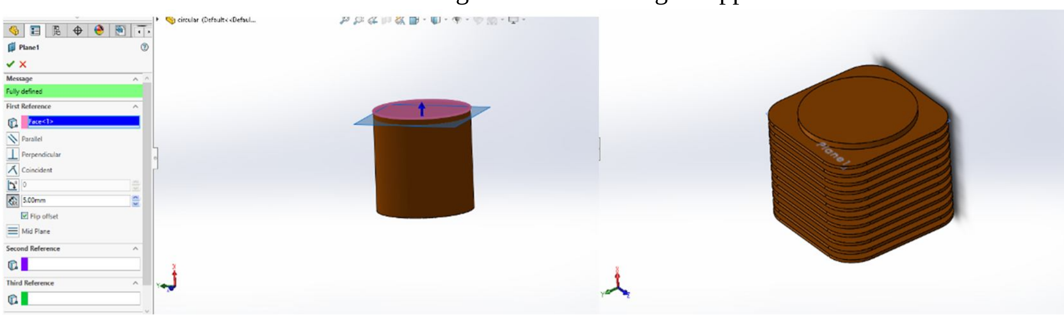

Fig 1. Geometry Modelling of Engine Cylinder Fins

B. Aluminium Alloy 2024

Aluminium 2024 is a high strength alloy that is mainly alloyed with copper. It has a high fatigue resistance and is usually applied in the cases when high structural integrity is demanded.

Material Properties
Young's Modulus: 7.31×10^{10}Pa
Poisson's Ratio: 0.33
Density: 2780 kg/m³
Yield Strength: 325 MPa & Thermal Conductivity: 121 W/m·K

C. Aluminium Alloy 6061

Aluminium 6061 is a common structural alloy that has a high resistance to corrosion, good weldable and balanced mechanical properties. Major alloying elements of it are hardened with magnesium and silicon through precipitation.

Material Properties
Young's Modulus: 6.89 × 1010Pa
Poisson's Ratio: 0.33
Density: 2700 kg/m³
Yield Strength: 276 MPa & Thermal Conductivity: 167 W/m·K

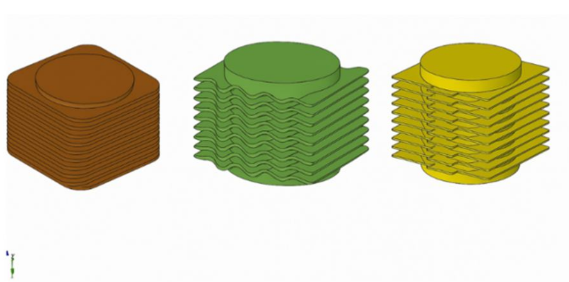

Fig 2. Final Model of Three Geometries

D. Structural Boundary Conditions

Static structural analysis is performed by applying a fixed support at the base of the cylinder to simulate attachment to the engine block. A uniform pressure load is applied on the fin surfaces to represent mechanical loads during engine operation. The outputs evaluated include total deformation, von Mises stress, strain, and factor of safety.

1) Fixed Support: - At the bottom of the cylinder, a rigid support was used, to which the cylinder would have been joined to the engine block. This restriction confines all the degrees of translational and rotational freedom and models a rigidly mounted cylinder.

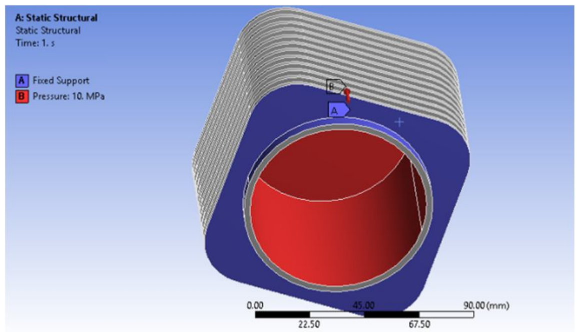

Fig 3. Fixed Support Applied at Cylinder Base

2) Pressure Load Application: - External pressure of 10 MPa was applied to fin surfaces to determine the structural integrity of each of the fin designs. • This replicates the forces produced when the engine is running because of combustion vibration, drag caused by airflow, and contact with the engine casing. • Pressure Type: Uniform pressure • Applied On: All fin surfaces and outer cylinder wall • Load Value: 10 MPa, increased gradually until the design reached a minimum safety factor ≈ of 1.5.

E. Thermal Boundary Conditions

Steady-state thermal analysis is conducted by applying a uniform heat flux at the inner surface of the cylinder wall to simulate combustion heat. Convective heat transfer is applied on the outer fin surfaces with an ambient air temperature of 28 °C and a convection coefficient representative of air-cooled engine conditions. Temperature distribution and heat flux are extracted for comparison. For both Al-6061 and Al-2024 fin models, the following boundary conditions were applied:

Heat Flux Applied on Inner Cylinder Surface Heat flux (inner wall): 25,000 $W \cdot m^{-2}$ This simulates the heat entering the cylinder wall during combustion. ➢ Convective Heat Transfer on Outer Fin Surfaces Convection (outer fin surfaces): $h = 25\ W \cdot m^{-2} \cdot K^{-1}$, $T_\infty = 28$ °C.

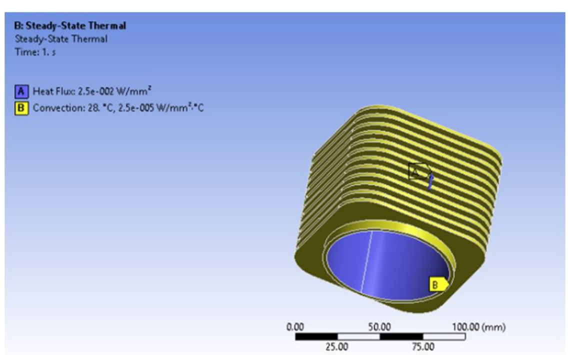

Fig 4. Thermal Boundary Conditions applied on Cylinder

IV. SIMULATION AND RESULTS

A. Structural Analysis

The structural results reveal that circular fins exhibit the lowest deformation and stress levels for both Aluminium 6061 and Aluminium 2024. Triangular fins show comparatively higher stress due to sharp geometric transitions, while sinusoidal fins exhibit moderate deformation and stress levels. Aluminium 2024 provides improved structural performance compared to Aluminium 6061 due to its higher yield strength.

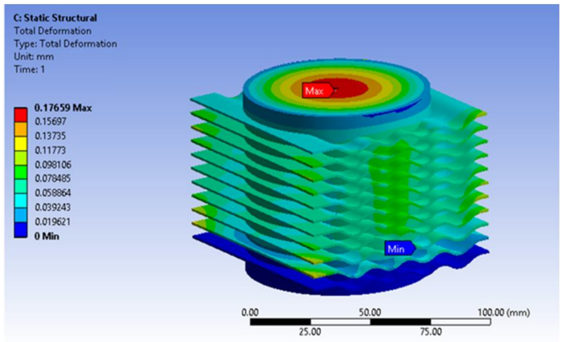

Fig 5. Total Deformation contour for Fin Geometries

B. *Thermal Analysis*

Thermal analysis indicates that triangular fins produce the highest heat flux and enhanced heat dissipation owing to increased surface exposure. Circular fins show the lowest heat transfer performance due to limited airflow disturbance. Sinusoidal fins improve convective heat transfer by inducing airflow turbulence, resulting in better cooling than circular fins while maintaining lower stress concentrations than triangular fins.

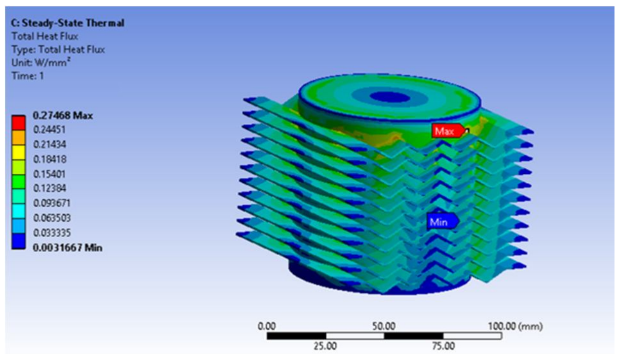

Fig 6. Heat Flux Contour

C. *Structural Analysis Results – Al 6061 (Triangular vs Circular vs Sinusoidal)*

Table 1. Static Structural Results for Al6061 at 10 MPa

Parameter	Triangular Fins	Circular Fins	Sinusoidal Fins
Deformation (mm)	0.18275	0.10894	0.17659
Stress (MPa)	166.65	98.456	180.12
Strain (–)	0.0029	0.0014293	0.0027562
Factor of Safety (FOS)	1.6562	2.8033	1.5323

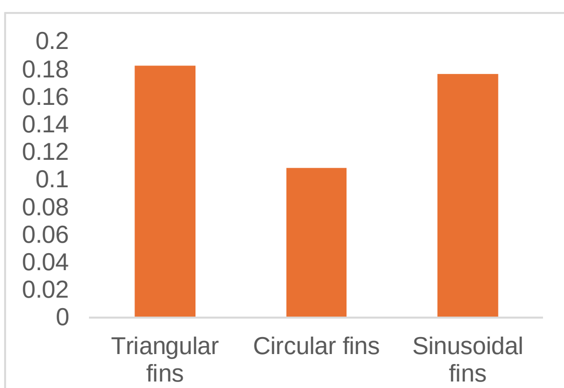

Fig 7. Comparison of total deformation for three geometries (Al-6061) in mm.

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D. Structural Analysis Results – Al 2024 (Triangular vs Circular vs Sinusoidal)

Table 2. Static Structural Results for Al-2024 at 10 MPa

Parameter	Triangular Fins	Circular Fins	Sinusoidal Fins
Deformation (mm)	0.17225	0.10268	0.16645
Stress (MPa)	166.65	98.456	180.12
Strain (–)	0.0027333	0.0013472	0.0025978
Factor of Safety	1.9502	3.301	1.8043

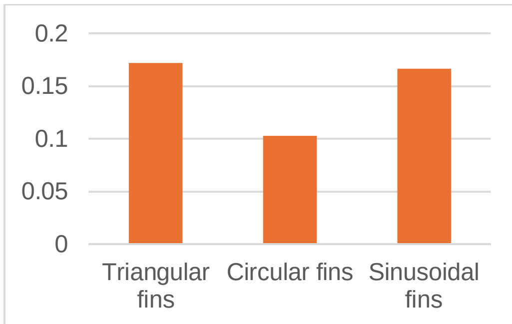

Fig 8. Comparison of Total Deformation for three geometries (Al-2024) in mm.

E. Thermal Analysis Results – Al 6061 (Triangular vs Circular vs Sinusoidal)

Table 3. Thermal Analysis Results – Al-6061

Parameter	Triangular	Circular	Sinusoidal
Total Temperature (°C)	274.15	238.49	287.67
Heat Flux (W/m²)	274680	170820	255700

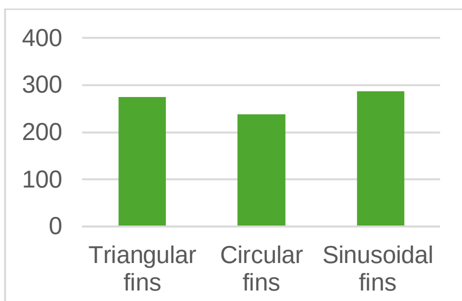

Fig 9. Temperature Comparison of fins in C^0

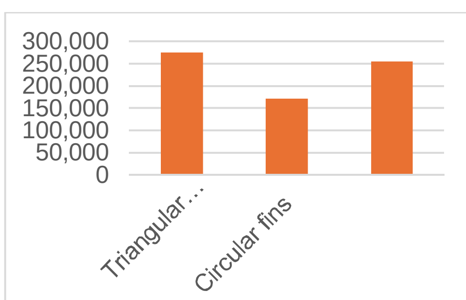

Fig 10. Heat Flux Comparison of fins in W/m^2K

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F. Thermal Analysis Results – Al 2024 (Triangular vs Circular vs Sinusoidal)

Table 4. Thermal Analysis Results – Al-2024

Parameter	Triangular	Circular	Sinusoidal
Total Temperature (°C)	274.15	238.49	287.67
Heat Flux (W/m²)	274680	170820	255700

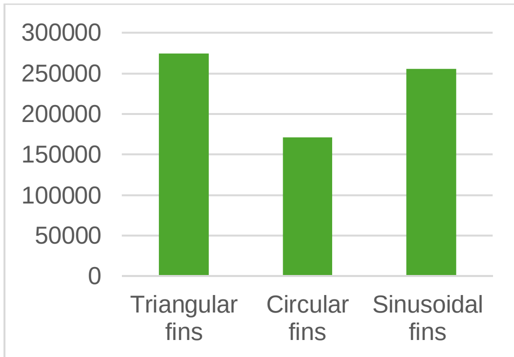

Fig 11. Temperature Comparison of fins in C^0

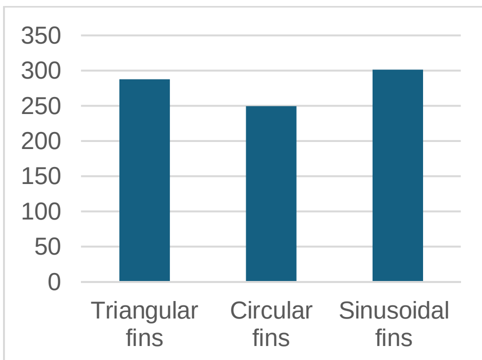

Fig 12. Heat Flux Comparison of fins in W/m^2K

G. Performance Trade-Off

A clear trade-off between structural integrity and thermal performance is observed. Circular fins are structurally superior but thermally less effective, while triangular fins provide maximum cooling at the expense of higher stress. Sinusoidal fins offer a balanced performance, making them suitable for practical engine applications where both strength and cooling are required.

V. CONCLUSION

A comprehensive numerical investigation has been carried out to evaluate the structural and thermal performance of air-cooled engine cylinder fins by varying fin geometry and material using ANSYS Workbench. Circular, triangular, and sinusoidal fin geometries fabricated from Aluminium 6061 and Aluminium 2024 were analysed under identical boundary and loading conditions. Based on the results obtained, the following key conclusions can be drawn:

A. Influence of fin geometry on structural performance

Circular fins consistently exhibited the lowest deformation and von Mises stress values among all configurations. The smooth geometry of circular fins minimizes stress concentration at the fin root, resulting in higher factor of safety and superior structural integrity. Triangular fins showed higher stress levels due to sharp geometric transitions, while sinusoidal fins demonstrated moderate stress distribution with improved load sharing compared to triangular fins.

B. Influence of fin geometry on thermal performance

Triangular fins provided the highest heat dissipation capability, as indicated by increased heat flux values, due to larger exposed surface area and sharper edges that enhance convective heat transfer. Circular fins showed the lowest heat transfer performance because of relatively uniform airflow and reduced turbulence. Sinusoidal fins enhanced convective heat transfer by inducing airflow disturbances, leading to better cooling performance than circular fins.

C. Effect of Material Selection

Aluminium 2024 offered improved structural performance compared to Aluminium 6061 owing to its higher yield strength, resulting in lower deformation and higher safety factors for the same fin geometry. Thermal performance trends remained primarily governed by fin geometry rather than material selection, although Aluminium 6061 showed marginally better heat conduction due to its higher thermal conductivity.

D. Recommended Configuration

Considering both thermal and structural requirements of air-cooled engine cylinders, sinusoidal fins fabricated from Aluminium 2024 emerge as a suitable design choice, offering an effective balance between cooling efficiency, structural safety, and practical applicability.

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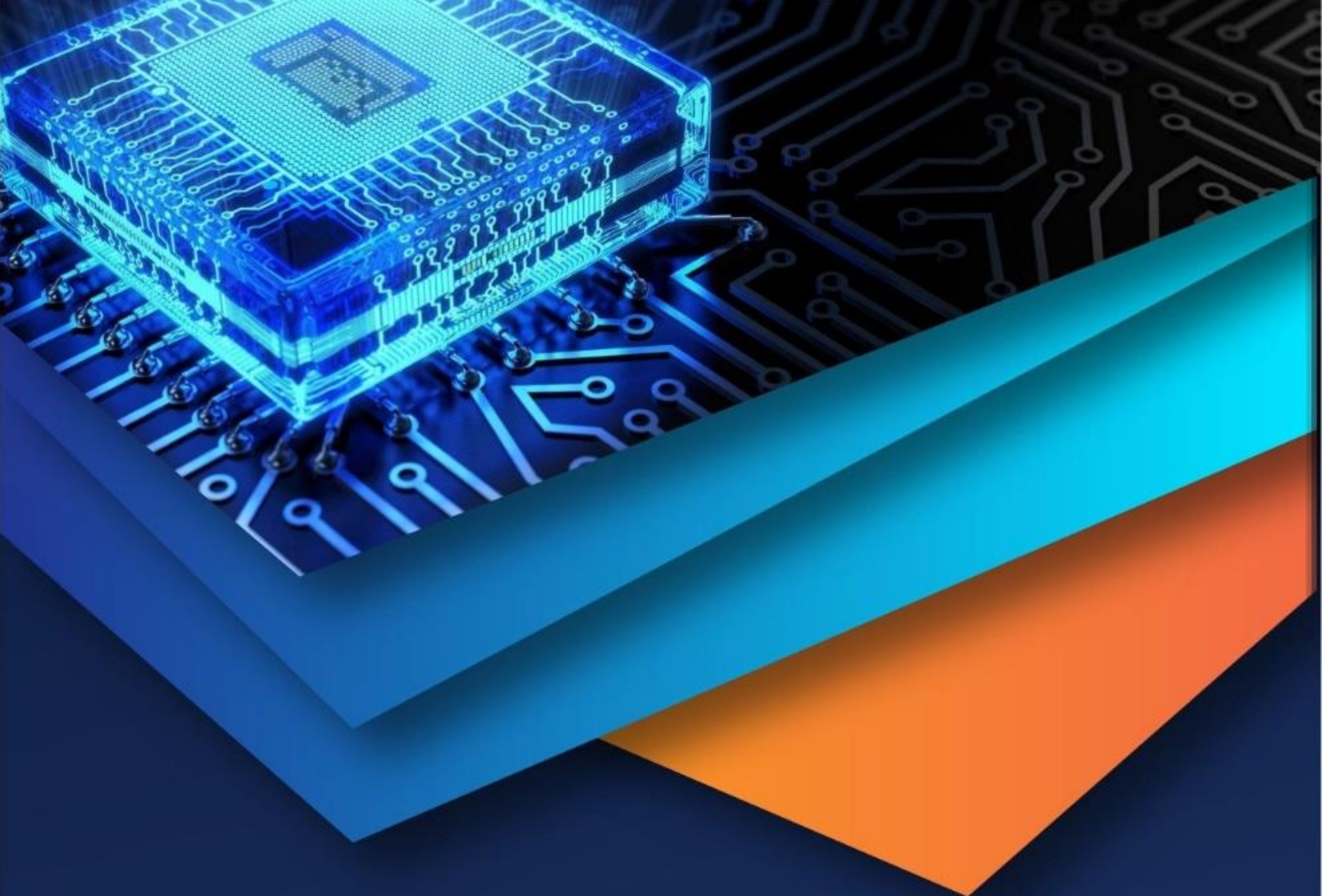

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