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Design, Analysis and Material Optimization of Hybrid Cooling for Turbine Blades

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Abstract: The main goal of the study is to optimize the material and processes utilized in turbine blades to improve their performance and the cooling efficiency. The most relevant area of interest is the hybrid cooling which initiates the thermal management problems of air internal turbine blade cooling by combining it with film cooling. The design has been done using Catia V5 and SolidWorks which includes parameter definitions that result in enhanced optimized blade geometry which further augmented by the increased air cooling. It is also paramount that the shape, size and placement of the cooling holes be controlled to improve thermal management while maintaining sufficient structural durability and strength. It is expected that with these refinements not only the heat dissipation ability of the blade improves but also the thermal loads on the surface will be reduced, which will enhance the lifespan and performance of the blade. Other analyses will seek to optimize materials to make them capable of enduring high temperatures while hybrid cooling resistance to thermal and mechanical stress. This study helps in the development of turbine blade cooling techniques to improve turbine operation performance and efficiency.
Keywords: Hybrid cooling, optimization, structural strength, cooling heat

I. INTRODUCTION

Gas turbine blades are important parts in the turbine stage of jet engines and power plants. They tap energy from high-temperature gases generated in combustion. When the gases flow over the blades they cause the turbine to rotate and transferring thermal energy to work. The mechanical energy is then used to operate the compressor and produce thrust or electricity. The blades are engineered to withstand extreme temperatures and rotational stresses without compromising aerodynamic efficiency. The shape and the alignment of their design are intricately engineered in order to ensure the maximum gas flow maximum extraction of energy and overall gas turbine system efficiency.

Gas turbine cooling is the methods employed to control the very high temperatures produced inside a turbine especially in parts such as blades, vanes and combustion chambers. These parts are subjected to hot gases that are usually above 1500^{o}C which are well above the melting point of even high-end materials such as superalloys. Without cooling these components would quickly fail due to thermal stress, oxidation and material degradation.

Cooling is needed to maintain structural efficiency and lifespan of turbine parts. Internal air cooling in which cooler compressor air is passed through hollow blades. The most commonly using techniques are impingement cooling, film cooling, transpiration cooling and thermal barrier coatings.

Cooling gas turbine requirement becomes increasingly necessary as new turbines seek greater thermal efficiency where they need to operate at high temperatures. Successful cooling enables turbines to operate under such harsh conditions safely achieving improved fuel economy, low emissions and more power output. Therefore, the cooling technologies are instrumental in the improvement and reliability of aircraft engines as well as industrial gas turbines.

Internal cooling is one of the methods in Fig.1 is applied in components that operate at high temperatures like turbine blades to regulate heat and avoid thermal deterioration. It implies circulating coolant in most cases air inside passages within the component. Some of the channels used pin fins, serpentine channels and holes for impingement to provide increased heat transfer. The cooling air picks heat from the walls of the metal and removes it lowering the structure's general temperature. Internal cooling is crucial in jet engines and gas turbines where parts are subjected to high temperatures providing reliability, extended life and maximum engine performance under extreme conditions.

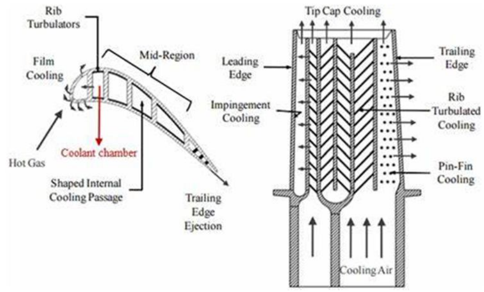

Fig.1. Internal cooling in blades

Film cooling is a method of cooling turbine blades in Fig.2 shows to shield them from high temperatures by inducing a thin insulating layer of cool air over the blade surface. This is done by blowing coolant normally compressed air through narrow holes or slots on the blades. The coolant creates a film that minimizes direct contact between the hot combustion gases and the blade and consequently reduces the metal temperature. Successful film cooling enhances blade life, thermal efficiency and enables turbines to run at elevated temperatures. The placement and geometry of cooling holes are key factors in maximizing cooling effectiveness and reducing aerodynamic losses.

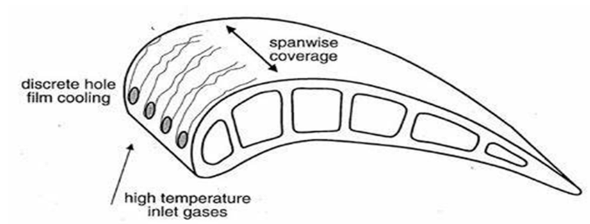

Fig.2. Film cooling in blades

The hybrid cooling refers to a method of thermal management that involves bending internal air cooling and film cooling to promote high-temperature parts heat shedding turbine blades. Internal cooling involves circulating the air within passages inside the part to lower its core temperature. Film cooling expenses coolant into surface holes and creates a safeguarding film across the surface. This dual strategy maximizes cooling efficiency by managing both internal and surface thermal loads which enables component to be used in extreme environments. Hybrid cooling enhances component longevity, thermal efficiency and engine overall efficiency which makes it a necessity in sophisticated aerospace and power generation applications.

II. TURBINE BLADES DESIGNS AND HOLE GEOMETRY

The study focuses on designing a turbine blade with appropriate design of the blade and also the selection of the airfoil. The NACA 2412 airfoil in Fig.3 is selected for its balanced aerodynamic properties which offering moderate lift with low drag making it ideal for turbine blade applications where efficiency and stability are crucial. Its cambered design enhances lift at lower angle of attack which is beneficial in cooling techniques relying on airflow control. The leading-edge outer radius of 44.5 mm is critical as it influences the airflow behaviour, heat transfer and structural strength at the front of the blade. A well-defined leading edge ensures smoother flow attachment and effective cooling, reducing thermal stresses and improving blade durability under high-temperature conditions.

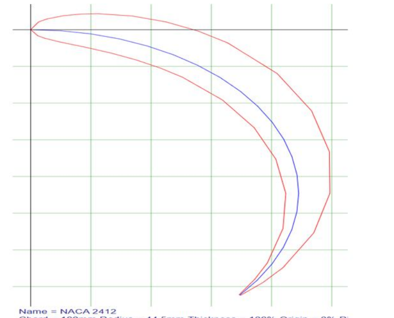

Fig.3. NACA 2414 airfoil profile

The no hole design of a turbine blade shown in Fig.4 is the most fundamental type where the blades does not have internal and external cooling passages. The design has a continuous cross-section throughout the blade which leading to a continuous aerodynamic profile that is structurally rugged and is easy to produce. The geometry is usually in the form of a streamlined airfoil shape which lead to maximum aerodynamic efficiency at high-speed flow conditions.

The blade has a dense root section to provide a safe mounting on the rotor disk and a tapering profile towards the tip to ensure stress distribution. The leading edge is to minimize flow separation while the trailing edge is reduced to keep wake formation low.

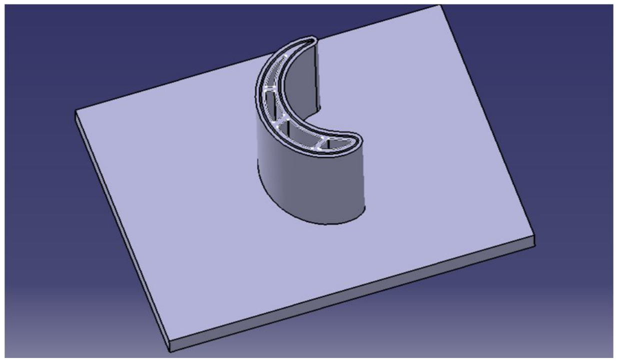

Fig.4. Un-holed blade design

The configuration of circular holes in turbine blades in Fig.5 and Table I shows the design parameters. It is important for maximizing the efficiency of hybrid cooling systems. These holes facilitate internal air cooling as well as film cooling which are vital to ensure structural integrity and thermal efficiency in high-temperature conditions. The circular holes were located in a way that facilitated even heat dissipation and minimized thermal gradients on the blade surface. The main goal was to optimize the hole arrangement to provide effective airflow distribution and maximum surface area coverage for cooling without sacrificing the blade aerodynamic profile or mechanical integrity. The design procedure was conducted with the CATIA V5 software enabling accurate 3D modelling and detailed depiction of the blade geometry and cooling hole arrangements. The code allowed for integration of design elements like smooth transition from the hole surface to the blade body with minimum stress concentration and structural continuity. The produced design forms a basis for conducting more detailed thermal and structural analysis setting the stage for performance enhancement by employing innovative cooling measures in turbine blades that perform in extreme environments.

Table I: Design parameters of circular hole

Sl No	Model Description	Dimensions
1	Leading edge outer radius	44.5 mm
2	Hole diameter	2 mm
3	Pitch	10 mm
4	Number of rows	15 mm
5	Hole shape	Circular

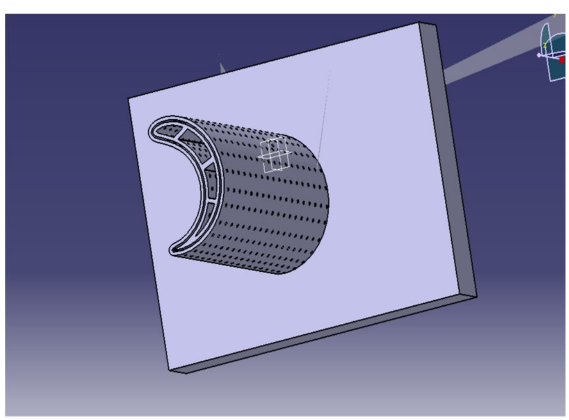

Fig.5. Circular holed blade design

Double hole turbine blade design shown in Fig.6 and Table II shows the design parameters which is a sophisticated method to enhance the efficiency of hybrid cooling systems by improving internal and film cooling mechanisms. The design features two closely spaced holes that operate together to provide improved coolant coverage and lower surface temperatures compared to single-hole configurations. The major objective of this design is to optimize the cooling efficiency while reducing the loss of structural integrity as a result of material removal. The holes were designed through SolidWorks that supported precise 3D modelling and advanced design fine-tuning. The unwanted holes are removed for making the design simpler. The software supported seamless incorporation of the holes into the curved blade surface without compromising the aerodynamic shape of the blade.
The distance and alignment of the holes were tailored to balance uniform distribution of cooling air and enhanced film coverage that is important in safeguarding the blade from elevated thermal loads during operation. Particular attention was paid to the fact that the design should not introduce excessive stress concentrations or interfere with airflow patterns. The double hole configuration therefore provides a solid basis for performance analysis and material optimization in high-temperature turbine conditions.

Table III: Design parameters of double hole

Sl No	Model Description	Dimensions
1	Leading edge outer radius	44.5 mm
2	Hole diameter	2 mm
3	Pitch	10 mm
4	Number of rows	9
5	Hole shape	Double circular

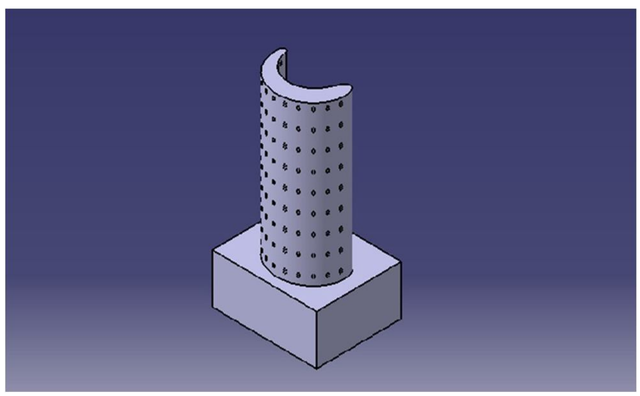

Fig.6. Double holed blade design

III. MATERIAL SELECTION AND ANALYSIS OF TURBINE BLADE DESIGN

A conjugate heat transfer (CHT) analysis was conducted in Ansys to simulate the thermal interaction between high-temperature combustion gases and external ambient air across the wall of a combustion chamber. The materials evaluated includes Inconel-718, Inconel-738, Ti-4Al-V6 and Ti-6242. The purpose of the study was to model the simulation heat transfer through solid and fluid domains to support material selection in high-temperature environments. The combustion chamber was exposed to an internal air temperature of 1600 K. The K-epsilon turbulence model was used to capture the effects of turbulent flow in both fluid regions ensuring a balance between computational efficiency and accuracy in predicting thermal and velocity fields.

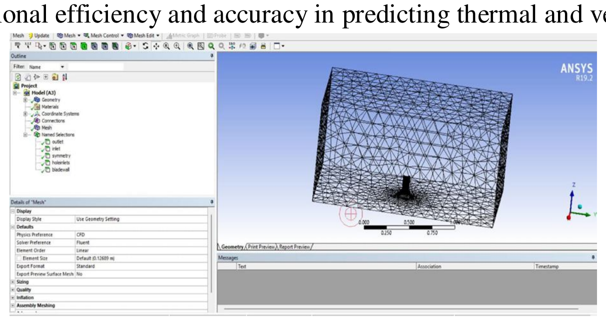

Fig.7. Meshing of the blade

In ANSYS the geometry was designed with appropriate thickness to accommodate heat transfer across solid wall. Fluid-solid interfaces were defined to enable heat conduction and convection. Meshing was refined as shown in the Fig.7 near walls to resolve boundary layer gradients effectively. Boundary conditions included specified inlet temperature and velocities for both hot and cold air with pressure outlets to facilitate flow development.

Table IIIII: Material Properties

Materials	Properties		
	Thermal Conductivity (W/m K)	Density (g/cm^3)	Specific Heat (J/kg K)
Inconel-718	11.4	8.14	425
Inconel-738	11.2	8.24	585
Ti-4Al-V6	6.7	4.4	562.3
Ti-6242	6.92	5.54	460

The thermal properties of the materials shown in Table III as conductivity, specific heat, and density were input to define the solid region. Steady-state simulations were run until convergence was achieved for temperature and flow parameters.

Table IVV: Specification of Analysis

Sl No	Boundary Conditions	Value
1	Inlet velocity	30 m/s
2	Hole inlet velocity	5 m/s
3	Temperature	1600 K
4	Viscous model	K-epsilon
5	Initialization	Hybrid initialization

Table IV shows the specification of analysis. The study setup enabled temperature distribution, heat flux and wall thermal behaviour providing a basis for assessing material performance in high-thermal-load environments without focusing on specific results as shown in Fig.8.

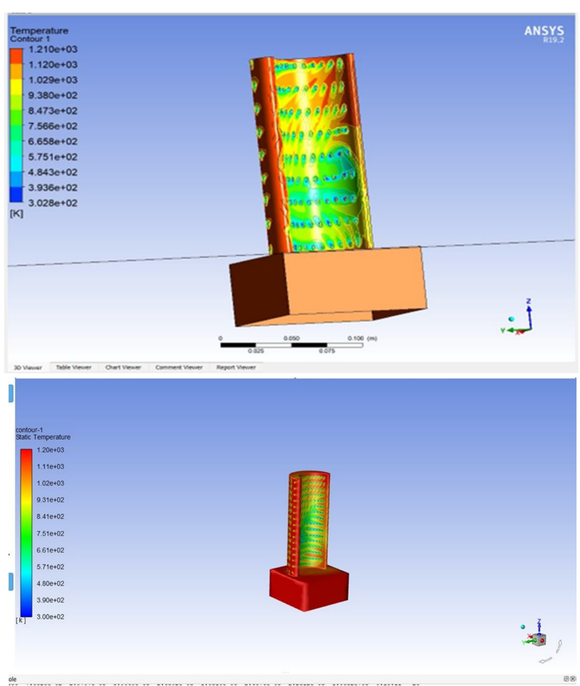

Fig.8. Analysis of the blade

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IV. MATERIAL OPTIMIZATION

Material optimization in Fig.9 aims at the selection and strengthening of materials to resist severe thermal and mechanical loads and enhance the effectiveness of hybrid cooling in turbine blades. Inconel-718, Inconel-738, Ti-4Al-V6 and Ti-6242 are the major materials under consideration which are selected based on their strength at high temperature, oxidation resistance and thermal fatigue behaviour. All these materials were tested against thermal conductivity, specific heat and density according to turbine operating conditions.

Inconel alloys as nickel-based super alloys possess great strength and high-temperature corrosion resistance hence are suitable for areas subjected to maximum thermal loading. Titanium alloys as Ti-4Al-V6 and Ti-6242 have a good strength-to-weight ratio and good thermal stability thus they are appropriate for cooler areas or where weight minimization is necessary. Optimization was achieved by correlating performance under hybrid cooling encompassing internal air cooling and film cooling. Thermal analysis through Ansys revealed the hot spots of thermal stress which influenced the placement of material. The aim is to employ heavier and more heat-capable alloys where necessary and lighter alloys elsewhere striking a balance between durability, efficiency and weight. This material-adaptive design enhances blade life and overall turbine performance.

MATERIAL	HOLE TYPE	INLET TEMPERATURE (K)	BLADE SURFACE TEMPERATURE (K)	PERCENTAGE REDUCTION IN TEMPERATURE
Inconel - 718	No Hole	1600	1600	
	Circular Hole		1127.814	29.51
	Double Hole		1428.852	10.7
Inconel - 738	No Hole	1600	1600	
	Circular Hole		1118.325	30.1
	Double Hole		1421.909	11.13
Ti - Al4 - V6	No Hole	1600	1600	
	Circular Hole		1119.564	30.03
	Double Hole		1450.562	9.34
Ti - 6242	No Hole	1600	1600	
	Circular Hole		1114.106	30.37
	Double Hole		1440.894	9.94

Fig.9. Optimized values from the Analysis

V. RESULT

On the basis of comparative examination of the designs of turbine blade cooling no holes, circular holes and double holes. The Fig.10 shows the optimal result by percentage reduction in temperature for different materials. The circular hole design was the most efficient in minimizing blade temperature. Out of the materials that were tested, Ti-6242 showed optimal performance with the circular hole design and experienced a substantial decrease in temperature of 30.37% in comparison with the no-hole and double holed models. This shows Ti-6242 has high thermal resistance and suitability with hybrid cooling methods. On the other hand, in the double hole configuration Inconel-738 revealed the best possible results with a temperature reduction of 11.13%. Though double hole geometries offered relatively moderate cooling, their performance was significantly lower than that of circular holes. Hence, the design of the circular hole with Ti-6242 is the most efficient pair to improve turbine blade thermal performance.

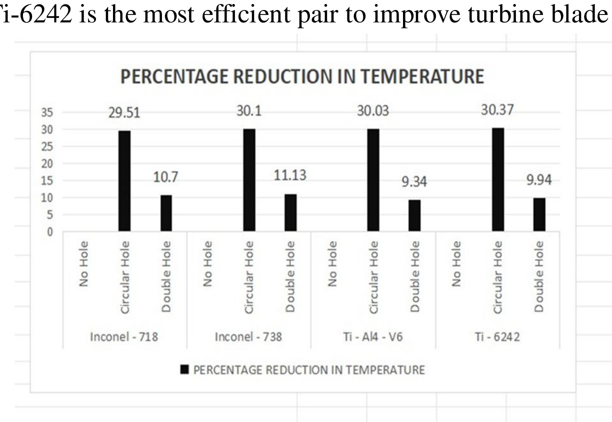

Fig.10. Percentage reduction graph

VI. CONCLUSION

The research highlights about the combination of internal air cooling and film cooling known as hybrid cooling the study aimed to optimize hole geometries in order to enhance heat transfer and minimize thermal stresses. The use of advanced materials like Inconel-718, Inconel 738, Ti-4Al-V6 and Ti-6242 was under consideration based on their higher thermal and mechanical properties at elevated temperatures. Designing performed with the use of CATIA involved the creation of various hole shapes and configurations to find out their influence on cooling performance. The following analysis phase which is carried out in Ansys will perform thermal simulation to analyze the efficiency of every geometry and material. The end target is to determine a best-of-breed cooling design and material combination that will maximize heat transfer, minimize thermal fatigue and guarantee turbine blade longevity under severe conditions. The present work has the key potential for break throughs in advancing turbine technology towards improved efficiency and reliability for aerospace and power generation sectors.

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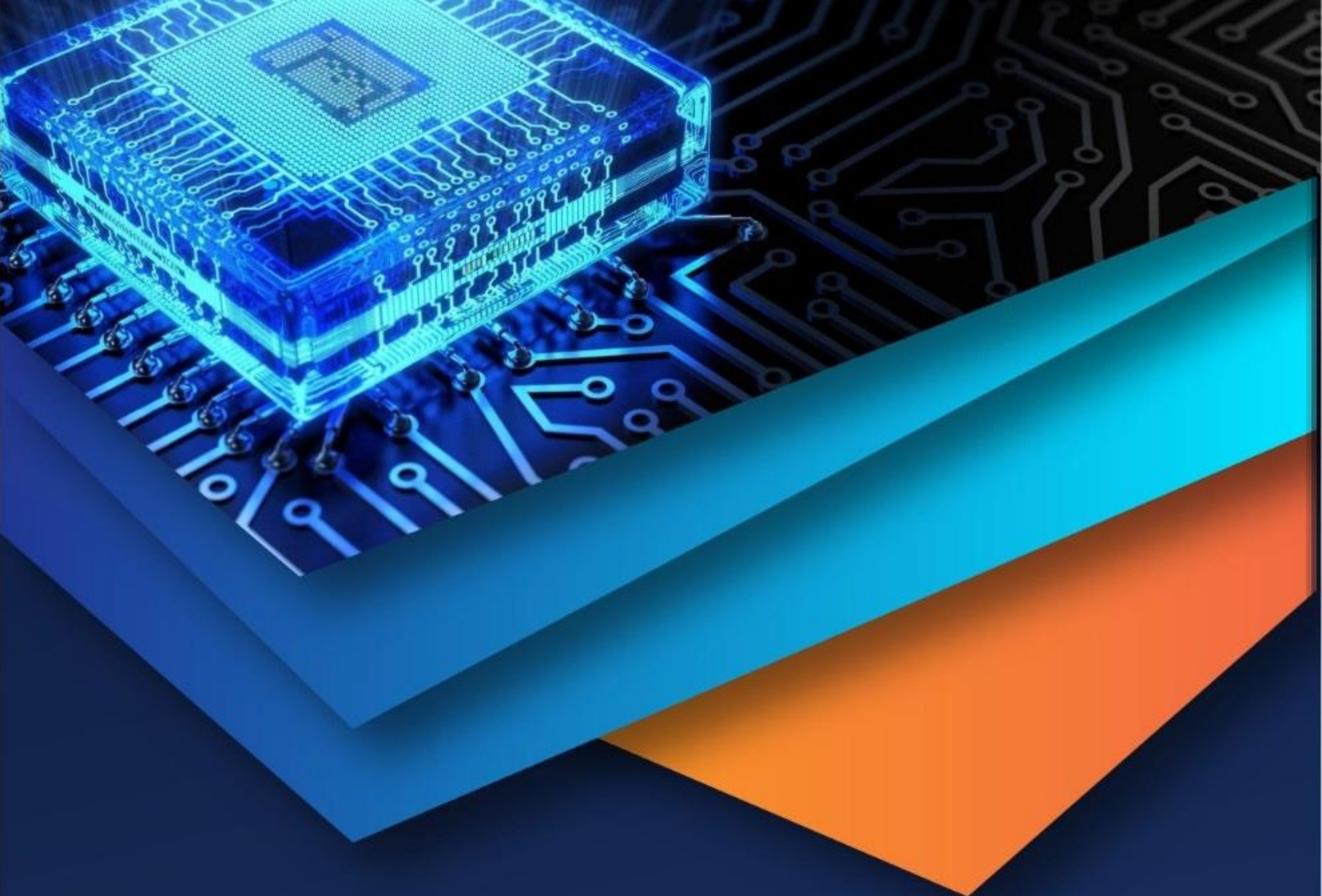

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