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Manufacturing of Flexible Printed Circuit Boards for MRI Systems

K Aksharaakruthi[1], M Puneeth[2], B Sukesh Kumar[3], V Megha Syam Gopal[4], T Niranjan[5]
[1, 2, 3, 4]B.Tech, Student, [5]Assistant Professor, Department of Mechanical Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, India

Abstract: This paper focuses on the advanced manufacturing of a flexible printed circuit board (PCB) specifically designed for use in magnetic resonance imaging (MRI) machines. Flexible PCBs offer unique advantages over traditional rigid counterparts, particularly in environments requiring space efficiency and dynamic applications. The flexibility of these PCBs allows for their integration into compact and curved spaces within the MRI system, optimizing space utilization and enabling superior design freedom in assembly. This paper explores the complete lifecycle of flexible PCBs (FPCs), focusing on material selection and the creation of multi-layered, highly conductive pathways for efficient signal transmission in high-resolution imaging. Key production stages include etching, drilling, plating, and lamination, with an emphasis on how these processes affect performance, reliability, and cost-effectiveness. Advanced manufacturing techniques, such as pneumatic presses for die cutting, CNC drilling for precision routing, and Automated Optical Inspection (AOI) for error detection, are employed in this work to ensure thermal and mechanical resilience. The resulting flexible PCB offers improved adaptability and reliability, enhancing performance in sophisticated medical imaging technology and contributing to more accurate diagnostics and patient care.

Keywords: Flexible PCB, advanced manufacturing, MRI machines, CNC drilling, AOI, thermal resilience, medical imaging, accurate diagnostics.

I. INTRODUCTION

In the demanding environment of an MRI machine, where powerful magnetic and radio-frequency fields are present, the flexible PCB must meet stringent performance requirements. It needs to ensure high levels of electromagnetic compatibility, maintain signal integrity, and exhibit exceptional durability. These performance goals are achieved through the use of advanced materials and thoughtful design that minimize signal loss and interference [1]. The flexible nature of the PCB not only enhances its adaptability to curved and compact spaces but also makes it more resilient to bending and vibrations, while maintaining electrical performance comparable to that of rigid PCBs [2].

Flexible Printed Circuits (FPCs) are integral to the functioning of Magnetic Resonance Imaging (MRI) systems, which are critical tools in modern medical diagnostics. MRI technology uses powerful magnetic fields and high-frequency radio waves to generate detailed images of the body's internal structures, making it essential for diagnosing a wide range of conditions [3]. However, the environment inside an MRI machine presents several challenges for the electronic components that support these processes. These components must operate in a high-magnetic field, be shielded from electromagnetic interference, and withstand mechanical stresses such as vibrations and bending. In this context, FPCs offer a number of advantages over traditional rigid printed circuit boards (PCBs). FPCs are designed to be flexible and adaptable, which makes them ideal for applications like MRI systems where space is limited and internal components need to be configured in irregular or compact spaces. Unlike rigid PCBs, which cannot conform to curved or tight areas, FPCs can be bent, folded, or twisted to fit within the precise geometries of an MRI machine. This flexibility enables more efficient use of space, reducing the overall size and complexity of the MRI system. Additionally, the ability to avoid unnecessary connectors and cables results in a more streamlined design, contributing to the lighter weight and more compact form factor of the MRI system. The use of FPCs in MRI systems also enhances electromagnetic compatibility (EMC). MRI machines operate in a high-magnetic field, which can cause interference with other electronic components.

Flexible PCBs are designed with advanced shielding techniques to protect sensitive components from external electromagnetic interference, ensuring that the MRI system performs at optimal levels without signal distortion or loss of accuracy. By addressing the limitations of rigid PCBs, flexible PCBs allow for a more efficient, reliable, and compact design of MRI machines. This leads to improvements in imaging performance, system durability, and ease of maintenance, ultimately contributing to better diagnostic capabilities and improved patient care. The integration of FPCs in MRI technology exemplifies the importance of innovation in electronic design, pushing the boundaries of medical imaging and advancing the overall field of healthcare [4].

Finite Element Analysis (FEA) combined with fatigue life assessment to enhance the reliability of FPCs in dynamic applications.

The research utilized an automated Abaqus/CAE plug-in and performed sensitivity analysis through OPTIMUS to identify critical design and material parameters impacting fatigue life[5]. The authors advocated for the broader adoption of flexible PCBs in electronics and emphasized the importance of improved training and awareness to fully realize their potential[6].By integrating advanced material science with practical applications, the research enhanced the functionality of flexible PCBs for diverse uses, including high-performance electronics and compact designs[7]. The experimental findings demonstrated that flexible PCBs exhibited superior resistance to water-induced conductivity loss compared to rigid counterparts, reinforcing their suitability for damp environments and critical applications [8].

This work addresses the limitations of traditional rigid PCBs in MRI applications and aims to develop a more flexible, reliable, and efficient electronic solution. The objective of this work is to design and manufacture a flexible printed circuit board (PCB) tailored for magnetic resonance imaging (MRI) machines. This work aims to optimize the properties through material selection, design and manufacturing processes, advanced manufacturing techniques. By focusing on these elements, the paper aims to create a flexible PCB that enhances the performance of MRI machines, contributing to more accurate diagnostics and improved patient care.

II. MANUFACTURING METHODOLOGY

The following sequence of manufacturing Process ensures high precision, reliability, and durability in flexible PCBs for advanced applications like medical devices and defense equipment.

A. Material Selection

Material selection is a critical step in engineering and manufacturing, involving the choice of materials that best meet the requirements of a product or application. The process considers factors like functionality, performance, cost, and environmental impact.Polyimide (PI) is the most commonly used base material for FPCs due to its outstanding thermal stability (up to 260°C) and mechanical strength. Copper foils can be electroplated or laminated onto the substrate. The thickness of the copper layer is crucial for the performance of the FPC, and it can range from (0.5 – 3) oz/ft^2. Copper is preferred for its reliability and ease of processing in flexible circuit designs.Epoxy-based Adhesives are used to bond the copper foil to the substrate material. Epoxy adhesives offer strong bonding, good chemical resistance, and can withstand high temperatures. Polyimide Films cover lay provides mechanical protection to the PCB while maintaining flexibility. FR-4 material (typically used for rigid PCBs) can be employed as a stiffener for specific applications requiring additional mechanical strength. ENIG (Electroless Nickel Immersion Gold) is a widely used surface finish that provides superior corrosion resistance and excellent solderability. It consists of a nickel layer for barrier protection and a thin layer of gold for solderability. Surface finishes also include immersion tin, immersion silver, immersion Gold etc. Solder Mask protective layer is applied to areas of the PCB where soldering is not needed. silkscreen layer is used for marking component locations and providing designations on the circuit board. Raw material cut is a process of cutting the materials selected as per the required panel dimensions. For this process machines used are CUT MASTER, Sheeler, Rosenthal Sheeter.Accurate cutting ensures proper fit for subsequent PCB manufacturing steps like drilling and etching

B. Drilling and Routing

After the raw material is cut to the required dimensions, it undergoes stacking to prevent heat damage during the subsequent drilling and routing process.**Stacking** groups multiple panels together to protect them from heat during drilling and routing. CNC Drilling creates holes for electrical connections (vias), components, and mechanical mounting. Routing process ensures that the PCB is accurately prepared with all necessary cavities and holes before moving on to subsequent steps like etching and component placement.

C. Chemical Process

The chemical process in FPCB manufacturing plays a crucial role in defining the electrical and mechanical properties of the finished product. It involves several steps to etch the copper traces, apply protective coatings, and prepare the circuit for assembly.

Electroless Plating is a crucial process as shown in Fig.1 in the manufacture of multi-layer Flexible Printed Circuit Boards (FPCBs), particularly for metallizing the walls of drilled holes (vias) to enable electrical connectivity between different layers of the board. The primary goal of electroless copper plating is to deposit a thin layer of copper on the interior walls of drilled holes. This copper layer serves as a seed layer for subsequent electroplating, enabling electrical continuity between the two sides of the PCB. This process ensures the creation of a conductive pathway, crucial for inter-layer communication in multi-layer PCBs.

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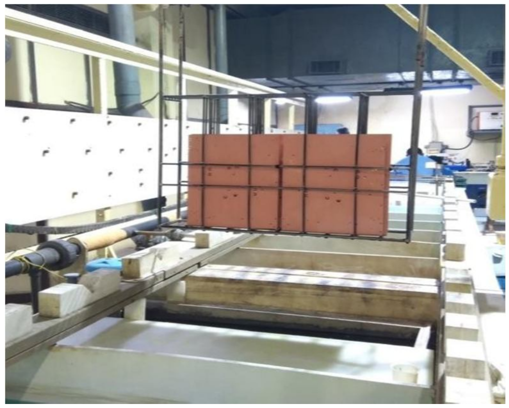

Fig.1. Electroless Plating

Flash plating shown in Fig.2 is an electrolytic process used to harden the copper layer already deposited during electroless copper plating. This process involves applying DC current to the plated copper, which promotes the deposition of additional copper onto the already copper-coated areas, increasing the thickness and enhancing the mechanical properties of the copper.

Fig.2. Flash Plating

D. Clean Room process (CRP)

A Class 1000 cleanroom is a controlled environment designed to maintain low levels of airborne particles, such as dust, microbes, and other contaminants, which could affect sensitive processes like PCB manufacturing, pharmaceuticals, or electronics assembly.
The dry film lamination shown in Fig.3 for PCB manufacturing is a critical step in ensuring accurate and high-quality circuit patterning.

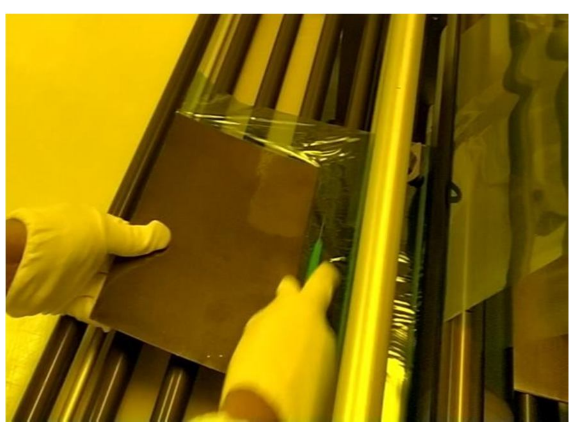

Fig.3. Dry Film Lamination

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The imaging process shown in Fig.4 in PCB manufacturing is a critical step for defining the circuit layout and transferring the circuit pattern onto the PCB surface. This process uses light exposure to selectively harden the dry film resist and create the desired trace patterns. Through this imaging process, the PCB layout is transferred onto the board, which then allows the copper etching process to create the conductive traces that form the electrical circuit. This is a crucial step to ensure precise circuit patterns and functionality.

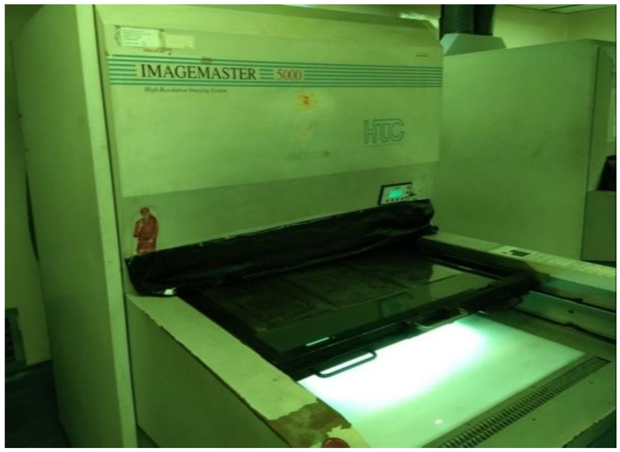

Fig. 4. Circuit Imaging

After the imaging process, the development as shown in Fig.5 stage begins to remove the unwanted dry film from the PCB panel, leaving behind the hardened film areas that correspond to the desired circuit pattern. This is a critical step to ensure the accuracy and quality of the final PCB design.

This stage ensures that the circuit pattern is accurately reproduced, preventing defects and ensuring high-quality, reliable PCB manufacturing.

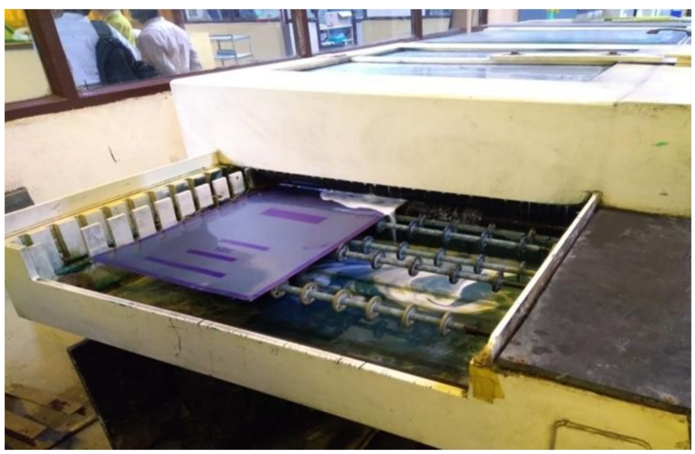

Fig.5. DFR Developing

E. Pattern Plating

Pattern plating is an electrolytic process used to deposit copper onto specific areas of a PCB, typically after the dry film imaging and development stages. The purpose is to form the circuit traces by plating copper onto the exposed areas that will remain, while the unexposed areas are left untouched.Pattern plating is essential for creating the high-precision, durable traces that define the functionality of the PCB, making it a crucial step in the overall PCB manufacturing process.

F. Tin Plating

Tin Plating is an electrolytic process used to deposit a layer of tin onto the copper traces on a PCB, providing essential protection to the copper surface during the etching process. The copper in the PCB is the primary medium for electrical conductivity, and protecting it ensures the integrity of the circuit and prevents unwanted corrosion or damage.

G. Etching and Stripping

The etching and stripping stage involves three key processes. The DFR stripping machine is used to strip off the dry film resist from the PCB panels after the tin plating process, leaving behind only the tin-plated circuit traces. This process is essential for ensuring that the dry film, which served as the mask during imaging, is removed to reveal the final copper circuit protected by the tin layer. PCB Copper etching is a crucial step in the manufacturing process that defines the circuit pathways on a PCB. The primary goal of etching is to remove unwanted copper from the PCB surface, leaving behind only the areas that will form the electrical traces for the circuit. This is done by exposing the PCB to an etching solution, typically a mixture of chemicals like ferric chloride or ammonium persulfate, which dissolve the exposed copper areas. Tin stripping is a critical process in PCB manufacturing that involves removing the tin layer applied during the plating process. This tin layer was initially used to protect the copper circuits during etching, ensuring that only the desired copper traces remain intact. In tin stripping, the goal is to strip the tin off the copper traces, exposing the final copper circuitry that will conduct electrical signals.

H. Cleaning and Quality Checks

The cleaning process in the manufacturing of Flexible Printed Circuit Boards (FPCs) is a critical step that ensures the quality and reliability of the final product. This process is designed to remove contaminants, such as oxides, residual chemicals, and moisture, which can adversely affect the performance of the circuits. Quality Checks is a key process used to inspect PCBs (Printed Circuit Boards) for manufacturing defects before components are assembled. This quality check ensures that the boards meet design specifications and are free of defects that could lead to failures in the final product.

I. Automated Optical Inspection (AOI)

It Uses cameras and pattern recognition algorithms to detect visual defects. AOI uses high-resolution cameras and image-processing algorithms to inspect PCBs. The system compares the scanned image of the board against a predefined reference image based on CAD data. The Resistivity of Solvent Extract (ROSE) Test is a method used to evaluate the cleanliness of a Printed Circuit Board (PCB) by measuring the ionic contamination present on its surface. Contamination can result from solder flux residues, cleaning agent residues, or other process-related impurities.

J. Finishing

The finishing process in the manufacturing of Flexible Printed Circuit Boards (FPCs) is a crucial phase that enhances the performance, durability, and reliability of the circuits. This process involves several key steps, each designed to ensure that the final product meets the required specifications for various applications. Below is a detailed overview of the finishing process for FPCs.

K. Surfaces Finishes

The application of surface finishes is a critical step in the finishing process of Flexible Printed Circuit Boards (FPCs). This step ensures that exposed copper pads and traces are protected from oxidation, contamination, and environmental factors, preserving their solderability and electrical performance. The choice of surface finish depends on factors like cost, application requirements, and the specific operating environment of the FPC.

L. Silk Screen (Legend Printing)

The silk screen process shown in Fig.6 is commonly used in PCB manufacturing to print legends (text, symbols, or markings) on the board. The use of a 120T mesh refers to the screen's mesh count, meaning there are 120 threads per centimeter.

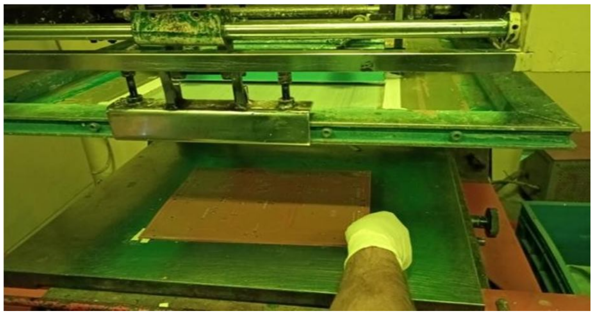

Fig.6. Silk screen (Legend Printing)

M. Inspection

The inspection process in the manufacturing of Flexible Printed Circuit Boards (FPCs) is essential for ensuring the quality and reliability of the final product.

This process involves various techniques and methods to identify defects, verify specifications, and confirm that the boards meet industry standards. A significant standard guiding this inspection process is IPC-A-600, which outlines the acceptability criteria for printed circuit boards. Below is a comprehensive overview of the inspection work done during FPC manufacturing, incorporating details about IPC-A-600.

The Flying Probe Test is a widely used electrical testing method for Flexible Printed Circuits (FPCs) to verify their electrical integrity. This non-contact, automated method uses multiple probes (typically 2 or 4) that move across the surface of the FPC to check for shorts, opens, and other electrical faults. The process is as follows:

The endurance, insulation resistance, impedance, peel strength, and voltage breakdown of a flexible printed circuit board (Flex PCB) are rigorously inspected using advanced testing machines. Endurance is evaluated through dynamic flexing equipment, ensuring the PCB withstands repeated bending cycles.

Insulation resistance is measured using high-precision insulation testers to verify electrical isolation between circuits. Impedance is analysed with network analysers to maintain signal integrity across varying frequencies. Peel strength is assessed through peel test machines to confirm the adhesive bond between layers, while voltage breakdown is tested using high-voltage dielectric testers to ensure safety and reliability under operational stresses.

III. RESULTS AND DISCUSSIONS

The flexible PCB designed and manufactured for MRI machines demonstrated excellent performance in several critical areas:

1) Electromagnetic Compatibility (EMC):
- Shielding and Grounding: The PCB exhibited exceptional electromagnetic compatibility, largely due to the effective employment of shielding and grounding techniques. These measures significantly reduced electromagnetic interference, ensuring that the MRI machine operated without any troubles or effects.
- Noise Reduction: The careful layout and planned placement of components minimized noise, which is important in maintaining the accuracy and consistency of MRI scanners.

2) Signal Integrity:
- High-Quality Signal Traces: The use of high-quality signal traces and controlled impedance was crucial in preserving signal integrity. This flexible design ensured that signals transmitted through the PCB were clear and precise, which is essential for the high-frequency applications typically in MRI machines.
- Differential Pairs: Implementing differential pairs helped to reduce electromagnetic interference and improved the overall signal quality, resulting in more accurate imaging results.

3) Thermal Management:
- Heat Dissipation: Efficient thermal management methodologies were employed to prevent overheating. The use of thermal vias and heat sinks ensured that heat generated by the electronic components was effectively dissipated, maintaining optimal performance even under the demanding conditions of MRI operation.
- Thermal Resistance: The materials selected for the flexible PCB exhibited excellent thermal resistance, which contributes to the overall stability and reliability of the PCB.

4) Durability:
- Mechanical Stress Tests: The PCB underwent rigorous mechanical stress testing, including repeated bending and flexing. It consistently maintained its structural integrity and functionality, proving its strength and reliability in dynamic conditions.
- Strain Relief: Techniques such as strain relief and strong connections were used to enhance the durability of the PCB, ensuring it could withstand the physical stresses encountered during MRI procedures.

The flexible PCB demonstrated superior performance in key areas such as electromagnetic compatibility, signal integrity, thermal management, and durability. These features made it highly suitable for the demanding and precise environment of MRI machines, ensuring the machine's operational efficiency and reliability for high-quality diagnostics. PROTOTYPE is shown in Fig.7.

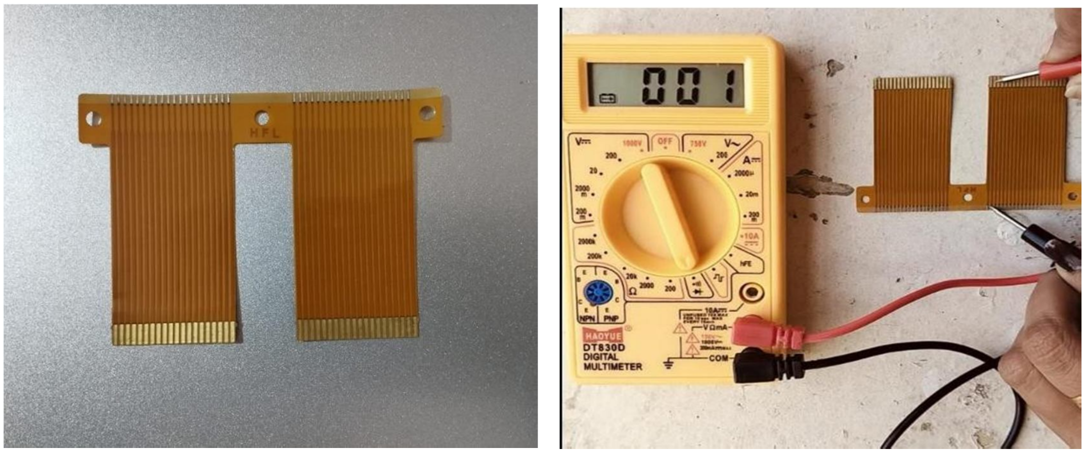

Fig.7. Working

The flexible PCB for MRI machines demonstrated exceptional performance across key areas, including electromagnetic compatibility (EMC), signal integrity, thermal management, and durability. Effective shielding, grounding, and strategic component placement minimized electromagnetic interference and noise, ensuring reliable operation. High-quality signal traces, controlled impedance, and differential pairs maintained signal clarity for accurate imaging. Advanced thermal management solutions, including thermal vias and heat sinks, efficiently dissipated heat, while thermally resistant materials ensured stability under demanding conditions. Additionally, rigorous stress testing and strain relief measures enhanced its durability, making it a reliable choice for the precise requirements of MRI systems.

III. CONCLUSION AND FUTURE SCOPE

The project on advanced manufacturing techniques for Flexible Printed Circuit Boards (FPCBs) demonstrates significant progress in meeting the unique demands of Magnetic Resonance Imaging (MRI) systems. By optimizing materials, processes, and integrating innovative technologies, it achieved enhanced flexibility, durability, and electromagnetic compatibility, enabling compact and reliable MRI systems for improved diagnostics. Advanced processes such as CNC drilling, automated inspection, and precision chemical treatments ensure high performance under stress, showcasing potential applications in aerospace and defence. This interdisciplinary effort highlights the role of emerging technologies in advancing medical imaging and setting benchmarks for high-performance, space-efficient electronics. 3D printing may represent the future of PCB manufacturing, offering customization, intricate designs, and rapid prototyping, driven by innovations in flexible, conductive, and biocompatible materials for applications like wearables and medical devices. While challenges such as material limitations, scalability, and resolution persist, hybrid approaches and advanced materials hold potential for addressing these issues in specialized applications.

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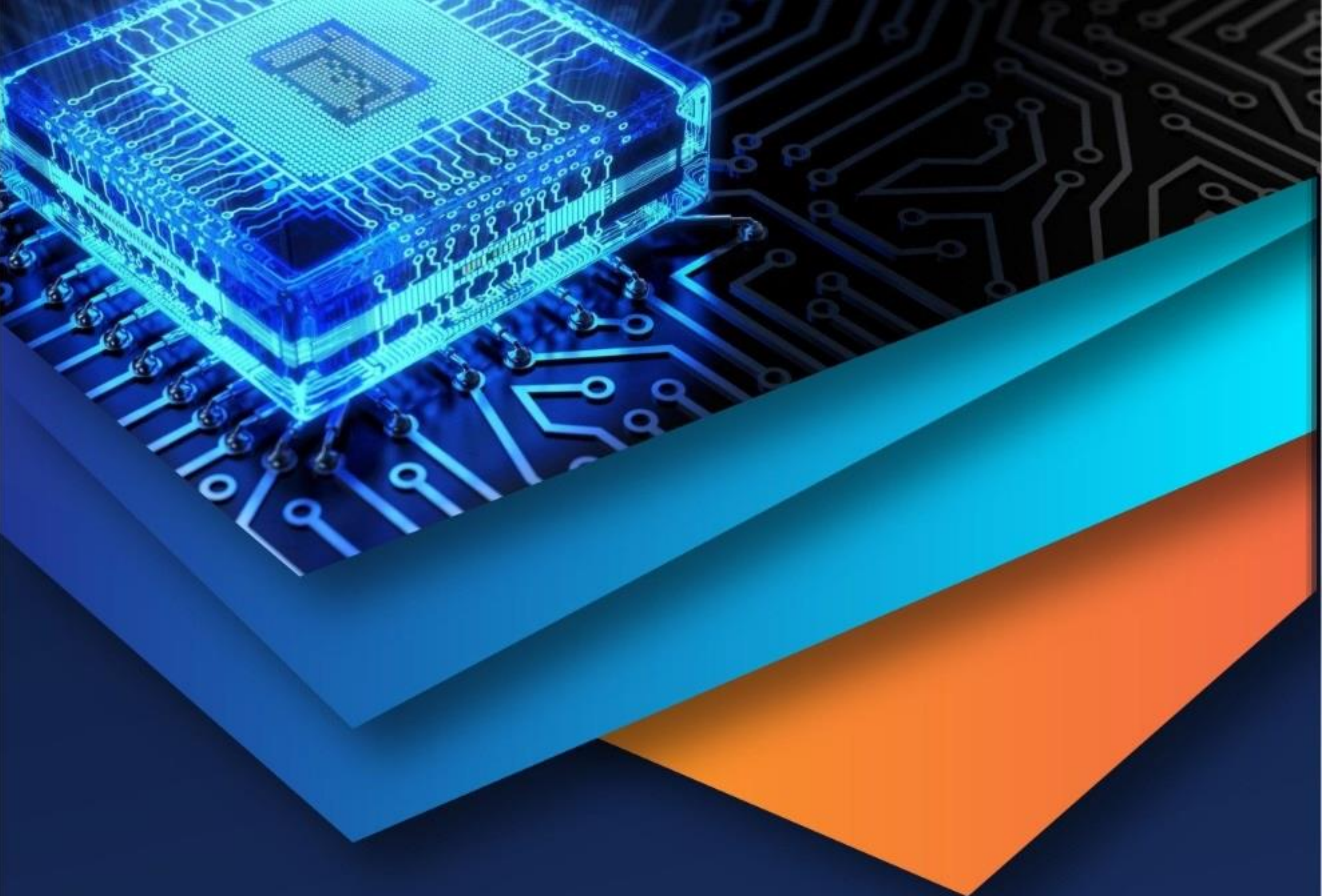

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