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Optimization of Process Parameters in 3D Printing for Validation of Mechanical Properties in End Product

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Abstract: This study presents a systematic methodology for optimizing process parameters in Fused Deposition Modelling (FDM), a widely used additive manufacturing method, to validate the mechanical feasibility of end-use parts printed from Polylactic Acid (PLA). The core objective is to overcome the common limitation of 3D printed prototypes by demonstrating that printed components can achieve mechanical performance comparable to conventionally produced parts. The research focuses on three key process parameters: infill pattern (Line, Grid, Honeycomb), infill density (50%, 75%, 100%), and raster angle (0°, 45°, 90°), which significantly influence structural integrity, load distribution, layer bonding, and overall durability. An extensive experimental design was formulated, involving the fabrication of standard test specimens (tensile, flexural, Charpy impact) conforming to ASTM D638, D790, and D256 specifications. Two specimens were fabricated per parameter combination to enhance statistical reliability, undergoing mechanical testing to assess tensile strength, flexural modulus, and impact resistance. Data analysis was performed using a Taguchi L9 orthogonal array, an efficient statistical design of experiments (DOE) technique, to identify the most significant parameters and their optimal levels for improved mechanical properties. The optimized parameters were then applied to manufacture an easily accessible consumer item, which was subsequently tested to ensure repeatability and functional applicability. The results confirm that PLA, processed under optimized FDM conditions, provides repeatable and adequate mechanical properties for actual use, reinforcing 3D printing's potential as a cost-effective, customizable, and sustainable manufacturing solution for functional components.

I. INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, has emerged as a revolutionary industrial production method, enabling the layer-by-layer fabrication of complex structures from digital designs. Unlike traditional subtractive manufacturing (e.g., cutting, drilling, milling), AM builds objects additively, minimizing material waste and offering unprecedented design freedom. Initially conceived for rapid prototyping, 3D printing has evolved into a pivotal technology across diverse sectors, including aerospace, healthcare, automotive, architecture, and consumer goods. Fused Deposition Modelling (FDM) is a particularly widespread additive manufacturing technique.

Despite its widespread employment, a key challenge in FDM, especially when using Polylactic Acid (PLA), is the inconsistency of mechanical properties in printed parts. This inconsistency often limits their application in end-use, load-bearing, or functional daily-life items. The mechanical properties of FDM-printed parts are highly sensitive to various process parameters, which have not been fully optimized or standardized.

This research directly addresses these challenges by deploying a systematic methodology to streamline process parameters in FDM to prove the mechanical feasibility of end-use parts. The work emphasizes three critical process parameters that significantly impact the structural integrity of printed parts: infill pattern (Line, Grid, Honeycomb), infill density (50%, 75%, 100%), and raster angle (0°, 45°, 90°). These parameters govern the internal structure and direction of material deposition, directly influencing load distribution, bonding between layers, and general durability.

The underlying drive of this work is to bridge the distinction between 3D printed prototypes and functioning real-world devices. The detailed aims of this study include:

- To evaluate the impact of printing parameters—specifically infill pattern, infill density, and raster angle—on the mechanical properties (tensile, flexural, and impact strength) of FDM 3D-printed PLA parts.
- To demonstrate FDM 3D printing's capacity as a cost-effective and efficient manufacturing method for producing mechanically reliable components.

- To prove that 3D-printed PLA parts, when manufactured under customized procedure settings, can be reliable, functional, and durable for daily-use applications.
- To determine the optimal combination of process parameters by analysing mechanical testing results using the L9 orthogonal array (Taguchi method).

Additive manufacturing also offers solutions to several key issues in daily life that are difficult or impossible to address with traditional manufacturing, such as replacing small broken parts for which replacements are unavailable, providing cost-effective and space-specific home utility and organization options, enabling customized ergonomic tools and accessories, and facilitating custom home repairs for legacy or non-standard installations. Examples of such parts include a mixer grinder jar coupler and an IR sensor housing

II. LITERATURE REVIEW

Additive Manufacturing (AM), broadly known as 3D printing, is a transformative industrial production method that allows for the creation of complex structures layer by layer from digital representations13. Its history spans several decades, evolving from early concepts to sophisticated modern applications.

A. History of Additive Manufacturing

The earliest known concept of 3D printing was introduced in 1981 by Dr. Hideo Kodama in Japan, proposing a layer-by-layer approach using UV-cured photopolymers. Charles Hull invented Stereolithography (SLA) in 1984, the first practical 3D printing technology, and also developed the widely used .stl file format. Hull founded 3D Systems in 1986, the first 3D printing company, and patented the SLA process, marking the beginning of commercial 3D printing by converting digital CAD data into physical parts using a UV laser to cure liquid photopolymer.

The 1990s saw rapid growth and the emergence of other AM technologies, including Fused Deposition Modelling (FDM) by Stratasys (founded by Scott Crump in 1989), which uses thermoplastic filament, and Selective Laser Sintering (SLS) by DTM Corporation, which fuses powdered materials with lasers.

The term "Additive Manufacturing" was coined as an umbrella term during this decade, primarily for rapid prototyping in automotive and aerospace industries.

The 2000s marked 3D printing's entry into biomedical and consumer markets, with significant advances in bioprinting and medical applications like prosthetics, dental implants, anatomical models, and the beginning of research into tissue engineering and organ printing. In 2005, Dr. Adrian Bowyer launched the RepRap Project, an open-source 3D printer capable of replicating most of its own components, democratizing 3D printing for hobbyists and makers. The first self-replicating printer (RepRap Darwin) was created in 2008, greatly expanding public interest.

The 2010s witnessed a consumer boom and industrial expansion. Affordable desktop FDM 3D printers from brands like MakerBot, Prusa, and Ultimaker became popular in the consumer market. Industrial expansion included aerospace (e.g., GE and Boeing printing engine components), healthcare (3D printed prosthetics, hearing aids, scaffolds for organs), and fashion/art (customized jewellery, shoes, art installations). Materials evolved beyond basic thermoplastics to composites, metals, ceramics, and biomaterials. In 2013, President Obama referred to 3D printing as "the next industrial revolution".

In the 2020s, AM integrated with Industry 4.0, leveraging automation, AI, and IoT. Advanced processes such as Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and multi-material/multi-colour printing gained prominence. Applications expanded into construction (3D printed houses and bridges), aerospace (lightweight, complex parts), medical (custom implants, surgical guides), and the food industry (3D printed chocolate, pizza, and meat alternatives).

III. METHODS & MATERIALS

A. Problem Statement

The significant potential of Fused Deposition Modelling (FDM) in additive manufacturing for producing tailor-made, low-cost parts is hindered by a critical issue: FDM-printed parts, particularly those made from Polylactic Acid (PLA), often lack consistent mechanical performance. This inconsistency restricts their use in end-use, load-bearing, or functional daily-life items. The root cause lies in the sensitivity of mechanical properties to 3D printing process parameters, which have yet to be fully optimized or standardized.

This project aims to resolve several key problems:

- The instability of mechanical properties of FDM-printed PLA parts due to variations in infill pattern, infill density, and raster angle.
- The absence of a rigorous approach to identify the optimal parameter combinations that enhance strength, stiffness, and impact resistance.
- The limited application of PLA for functional products due to uncertainties regarding its durability under practical loading conditions.
- The time and material wastage resulting from trial-and-error approaches without statistical verification.
- The lack of verification of optimized process conditions on real-life, consumer-grade finished products.

To overcome these challenges, this project employs a structured experimental approach utilizing ASTM-standard specimen testing and Taguchi's L9 orthogonal array to determine optimal process settings. Furthermore, it extends validation by applying these settings to a real-world product, confirming the feasibility of using 3D-printed PLA parts as reliable alternatives in everyday applications.

B. Methodology Overview

The overall methodology follows a systematic flowchart60. It begins with the selection of infill pattern, density, and raster angle, followed by the design and printing of test specimens, mechanical testing, Taguchi analysis, identification of optimal parameters, printing of end-use products, validation, and concludes with the determination of suitability for daily-use applications.

- Material: Polylactic Acid (PLA), a biodegradable plastic, was chosen as the material for this study1.
- Process: Fused Deposition Modelling (FDM) was the additive manufacturing method employed1.

C. Process Parameters

The research focused on three key process parameters:

- Infill Pattern: Line, Grid, Honeycomb
- Infill Density: 50%, 75%, 100%
- Raster Angle: 0°, 45°, 90°

During the 3D printing process, the PLA filament was extruded from a heated nozzle maintained at a constant temperature of 210°C, and deposited onto a heated build platform kept at a constant temperature of 60°C. Other slicing parameters, apart from the tested variables (infill pattern, density, and raster angle), were kept constant to minimize process-induced variability. Specimen positioning on the build platform was carefully planned to reduce support structures and achieve desired material grain orientation relative to applied mechanical loads.

D. Experimental Design

To efficiently analyse the influence of the three process parameters, each with three levels, on the mechanical properties of 3D-printed PLA specimens, a Taguchi L9 orthogonal array was employed [1]. This allowed for the study of three factors at three levels using only nine experimental runs, significantly reducing the number of experiments compared to a full factorial design (which would require 27 runs). Each of the nine rows of the L9 array represented a unique combination of the chosen parameters.

E. Specimen Design

Standard test specimens were designed based on ASTM specifications to ensure uniformity, replicability, and adherence to industrial standards. The specific standards used were:

- Tensile Testing: ASTM D638, employing a "dog-bone" configuration with defined dimensions (gauge length, width, thickness) to ensure uniform stress distribution and accurate measurement of tensile strength, elongation, and modulus
- Flexural Testing: ASTM D790, using rectangular test specimens with specified length, width, and thickness for three-point bending tests. This measures flexural strength and modulus, indicating resistance to bending loads.
- Charpy Impact Testing: ASTM D256, utilizing notched, typically rectangular bar specimens with defined notch geometry and depth to provide a controlled point of fracture initiation3.... This enables measurement of the material's resistance to impact forces.

Two specimens were fabricated for each test type and for each individual combination of process parameters to account for variance and enhance statistical reliability. The STL files for these geometries were created in accordance with the ASTM dimensional standards and then sliced using Prusa Slicer software6465. After printing, support structures were carefully removed, and specimens were visually inspected for defects before mechanical testing.

F. Mechanical Testing

Mechanical properties (tensile, Charpy impact, and flexural) of the 3D-printed PLA specimens were tested as per ASTM standards.

- Tensile Strength: Measured using a universal testing machine according to ASTM D638. A controlled tensile load was applied until specimen failure, measuring tensile strength, elongation at break, and Young's modulus [2].
- Charpy Impact Resistance: Determined with an Charpy impact tester on notched samples, as per ASTM D256. This quantified the energy absorbed upon fracture by a swinging pendulum.
- Flexural Strength: Tested using a three-point bending test fixture on a universal testing machine, conforming to ASTM D790. The centre of the specimen was loaded, and its deflection was recorded until failure or a specific strain.

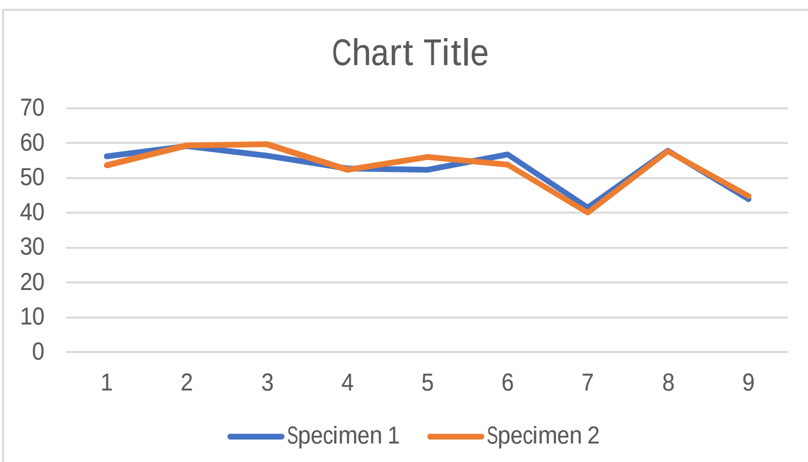
G. Analysis

The collected mechanical property data (tensile strength, elongation, impact strength, flexural strength, flexural modulus) were analysed using Analysis of Variance (ANOVA). This statistical method allowed for the determination of the statistically significant effects of each parameter and their interactions on the measured outcomes. This analysis identified optimal parameter settings that yielded the desired mechanical properties for the 3D-printed PLA end product and provided insights into the relative contribution of each factor.

IV. RESULTS & DISCUSSIONS

The experimental design, based on the Taguchi L9 orthogonal array, allowed for an efficient evaluation of the selected process parameters on the mechanical properties of FDM 3D-printed PLA specimens. The nine experimental runs, each tested with two replicates for tensile, flexural, and Charpy impact strength, yielded comprehensive data.

1) Tensile Test Results



Tensile Test Graph

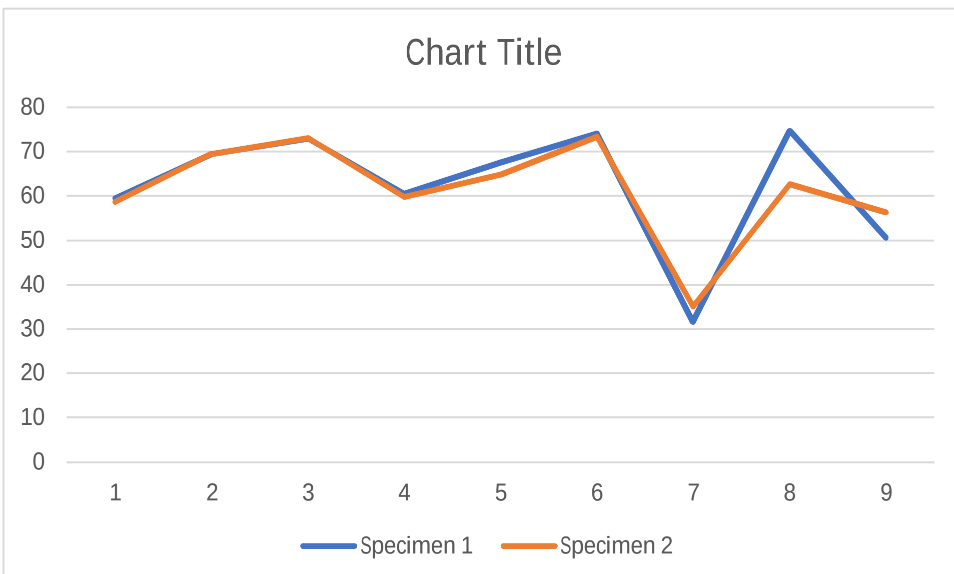
The above graphs show the tensile strengths of specimens with various process parameters.

Tensile Test				Specimen 1	Specimen 2	Avg
Exp. No.	Infill Pattern	Infill Density	Raster Angle	N/mm^2	N/mm^2	
1	Linear	50%	0°	56.29	53.69	54.99
2	Linear	75%	45°	59.1	59.27	59.185
3	Linear	100%	90°	56.43	59.79	58.11
4	Grid	50%	45°	52.73	52.35	52.54
5	Grid	75%	90°	52.45	56.08	54.265
6	Grid	100%	0°	56.77	53.79	55.28
7	Honey comb	50%	90°	41.59	40.1	40.845
8	Honey comb	75%	0°	57.82	57.7	57.76
9	Honey comb	100%	45°	43.83	44.76	44.295

Tensile Test Results

The above table display the result of Tensile Strength Test conducted on ASTM D638 specimen. With optimized parameters highlighted in yellow.

2) Flexural Test Results



Flexural Test Graph

The above graphs show the flexural strengths of specimens with various process parameters.

Flexural Test				Specimen 1	Specimen 2	Avg
Exp. No.	Infill Pattern	Infill Density	Raster Angle	N/mm^2	N/mm^2	
1	Linear	50%	0°	59.44	58.65	59.045
2	Linear	75%	45°	69.47	69.52	69.495
3	Linear	100%	90°	72.94	73.04	72.99
4	Grid	50%	45°	60.5	59.78	60.14
5	Grid	75%	90°	67.56	64.79	66.175
6	Grid	100%	0°	74.14	73.34	73.74

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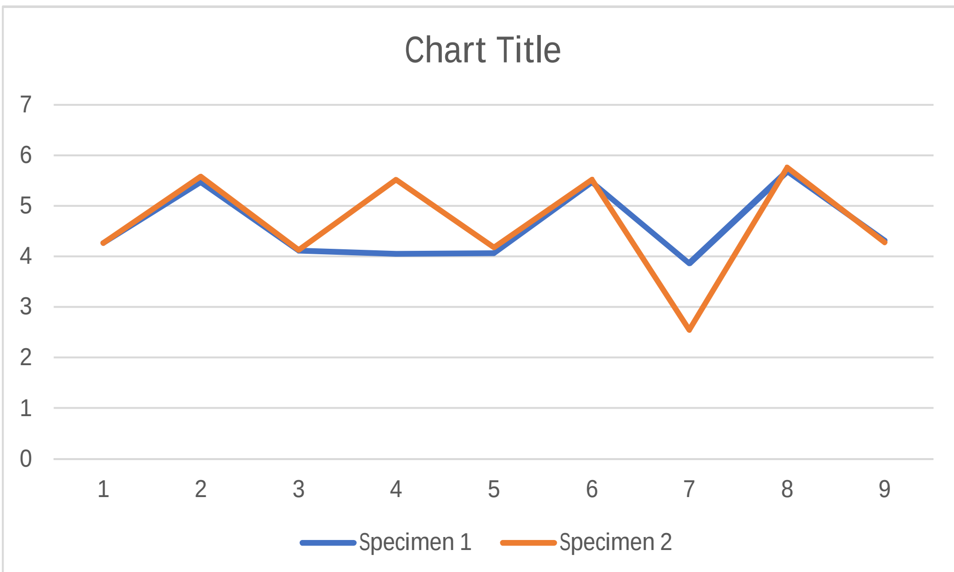
7	Honey comb	50%	90°	31.6	35.07	33.335
8	Honey comb	75%	0°	74.62	62.63	68.625
9	Honey comb	100%	45°	50.45	56.25	53.35

Flexural Test Results

The above table display the result of Flexural Strength Test conducted on ASTM D790 specimen. With optimized parameters highlighted in yellow.

3) Charpy Impact Test



Charpy Impact Test

The above graphs show the Charpy Impact test energy required to develop fracture on specimens with various process parameters.

Charpy Impact

Charpy Impact Test				Specimen 1	Specimen 2	Avg
Exp. No.	Infill Pattern	Infill Density	Raster Angle	Kj/m^2	Kj/m^2	
1	Linear	50%	0°	4.27	4.27	4.27
2	Linear	75%	45°	5.47	5.58	5.525
3	Linear	100%	90°	4.12	4.13	4.125
4	Grid	50%	45°	4.06	5.52	4.79
5	Grid	75%	90°	4.07	4.18	4.125
6	Grid	100%	0°	5.47	5.52	5.495
7	Honey comb	50%	90°	3.87	2.55	3.21
8	Honey comb	75%	0°	5.69	5.76	5.725
9	Honey comb	100%	45°	4.32	4.28	4.3

Test Results

The above table display the result of Charpy Impact Test conducted on ASTM D256 specimen. With optimized parameters highlighted in yellow.

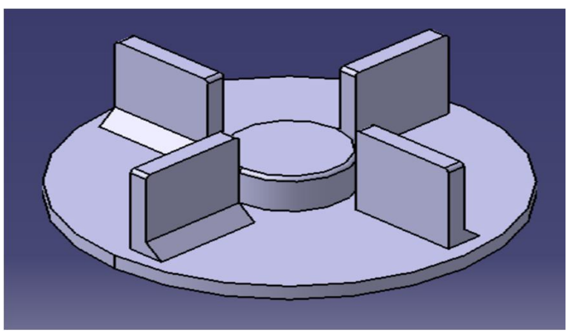
A. Identification of Optimal Parameters

The optimal combinations of parameters for each type of mechanical test are summarized:
Tensile Test: Optimal combination was Linear infill, 75% infill density, and 45° raster angle.
Flexural Test: Optimal combination was Grid infill, 100% infill density, and 0° raster angle.
Charpy Impact Test: Optimal combination was Honeycomb infill, 75% infill density, and 0° raster angle.

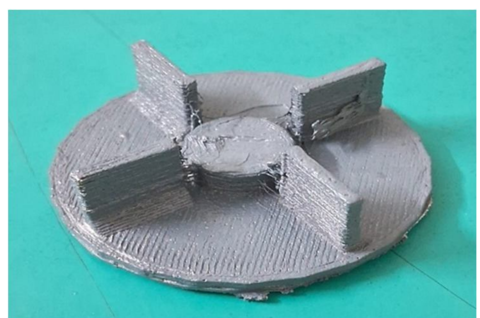
B. 3D Printing of End-Use Product with Optimized Parameters

Following the determination of the best parameter combinations through L9 orthogonal array testing and ANOVA, these optimized settings were applied to 3D print actual end-use products80. This final step served as a crucial validation of the optimization process, demonstrating the practical applicability of the determined parameters in fabricating functional components with improved mechanical properties80. The validation showed that the optimized PLA parts could indeed possess the desired performance characteristics identified during the specimen testing phase.
Two specific end-use products were chosen for this validation:

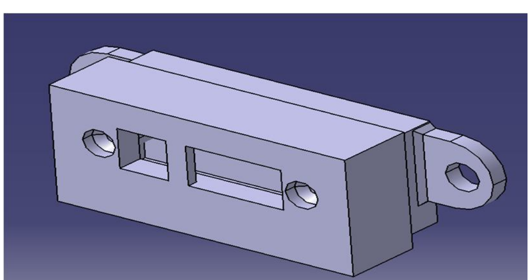
1) IR Sensor Housing: This component was selected as a suitable test to validate the optimized 3D printing parameters10. By printing this working component using the optimal infill structure, density, and raster angle for PLA, its structural integrity and functionality in actual application could be assessed. This approach effectively bridges the gap between material-level validation of mechanical properties and the functional specifications of a finished product, proving the efficacy of the optimization process in delivering desired performance in a given application. Applications for an IR Sensor Housing include robotic arms, assembly lines, and safety systems.
2) Mixer-Grinder Coupler: This real-world component was also chosen to validate the optimized 3D printing parameters. Fabricating this functional part with the optimal combination of infill pattern, infill density, and raster angle for PLA allowed for assessment of both structural durability and operational performance under actual working conditions11. This validation demonstrates how the optimized 3D printing settings translate into reliable, application-ready components, proving the success of the optimization process in achieving desired performance in a practical use-case for household appliances.



Mixer-Grinder Coupler CAD Model



3D Printed Mixer-



IR Sensor Housing CAD Model

3D Printed IR Sensor Housing

V. CONCLUSION

This study marks a significant step in transforming 3D printing from an empirical practice to a science-based process by optimizing key parameters such as infill pattern, infill density, and raster angle for FDM-printed PLA components. Using a systematic experimental design (Taguchi L9 orthogonal array) and ASTM-standard mechanical testing, it identified the optimal combinations that enhance tensile, flexural, and impact strengths. The successful production and validation of real-world parts like an IR sensor housing and mixer-grinder coupler demonstrated the practical reliability and repeatability of these settings. The research highlights FDM 3D printing with PLA as a cost-effective, customizable, and sustainable solution for producing functional components with dependable mechanical integrity for demanding applications.

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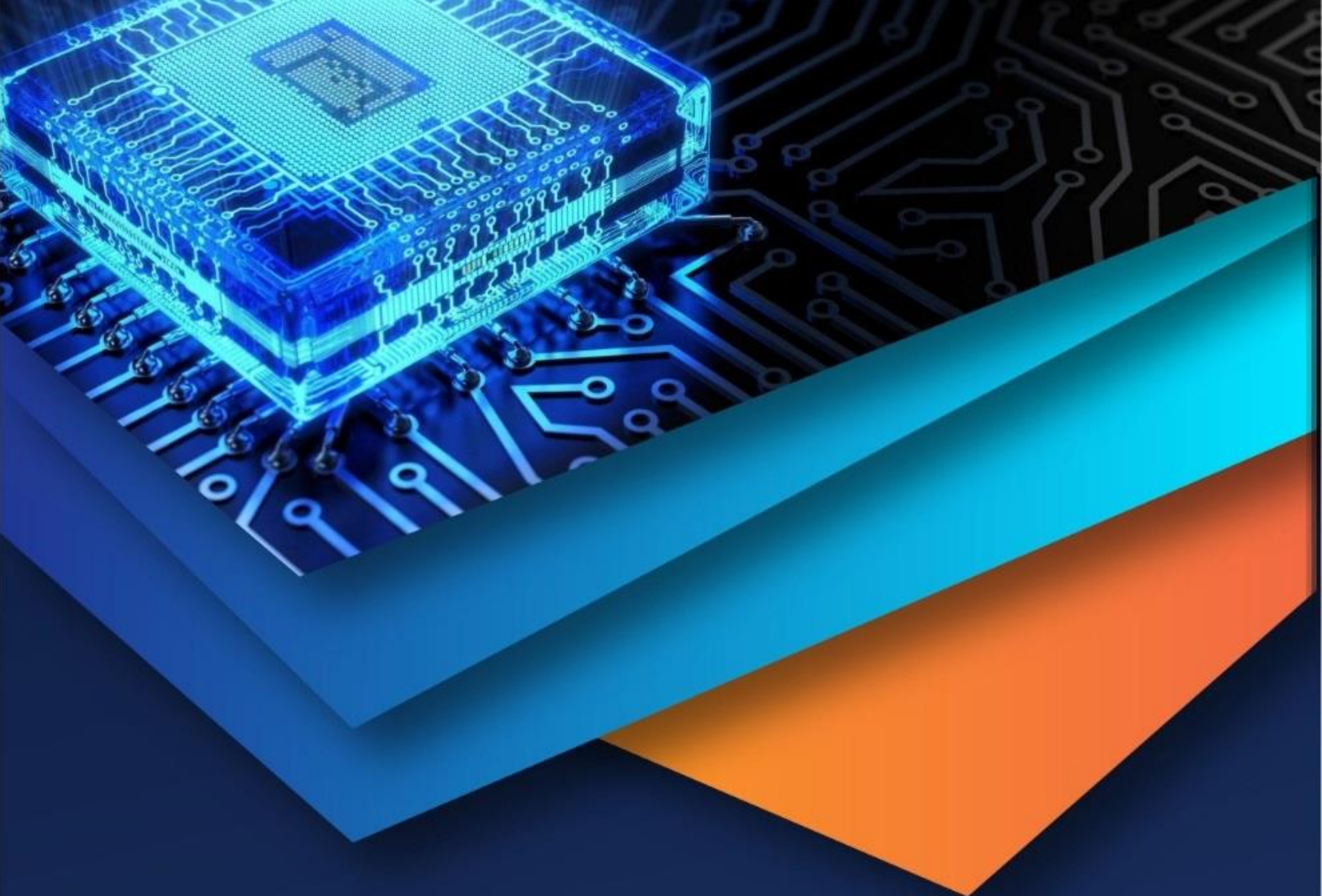

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