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Topology Optimisation of Piston

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Abstract: This research paper presents a comprehensive study on the topology optimization of a piston component manufactured through 3D printing technology. The study employs a combination of SolidWorks and ANSYS software to model and simulate the piston's structural behavior under different loading conditions. The optimized piston design is produced using PLA material through Ultimaker Cura software. The topology optimization process involves defining the design constraints and objectives, which are optimized to produce an optimal design with reduced weight while maintaining the required structural integrity. The paper investigates the effects of different loading conditions on the piston's structural performance and shows how the optimized design can enhance the piston's mechanical properties. The results show that the topology optimization process results in a piston design that reduces weight while maintaining the required strength and performance, thereby enhancing the efficiency of the 3D printing process. The study contributes to the growing body of research on the use of topology optimization in additive manufacturing and provides insights into the practical implementation of this approach in piston design.
Keywords: Piston, Topology Optimisation, Efficiency, PLA

I. INTRODUCTION

Modern engines use a variety of techniques, such as turbocharging (downsizing), high compression ratios, and improved spark ignition systems, to maximise engine efficiency, meet stringent engine pollution emission standards, and reduce fuel consumption. Higher specific loads are thus experienced, which raises the mechanical and thermal loadings on engine components. Designing high-performance pistons via topology optimisation has gained popularity in recent years. To get the best design, topology optimisation entails building a mathematical model of the piston's shape, specifying the performance requirements, and then gradually eliminating material from the model. Making a 3D model of the piston geometry, comprising the crown, skirt, ring grooves, and pin boss, is the first step in the optimisation process. In order to simulate the engine's working circumstances, the model is then subjected to a variety of loads and boundary conditions, including combustion pressure, inertial loads, and thermal loads. The optimisation system then analyses the model using mathematical techniques to spot regions where material can be reduced without compromising the strength and stiffness of the piston. The programme tries to reduce the piston's weight while preserving its performance and structural integrity. Finite element analysis (FEA), which uses numerical techniques to address challenging engineering issues, can be used to carry out the optimisation process. A lightweight piston design that satisfies performance requirements, such as decreasing stress and deformation, while reducing the piston's mass, is the end result of the topology optimisation process. The piston's lighter mass results in less friction and inertia, which enhances engine performance, fuel efficiency, and emissions. To improve heat transfer and lower the chance of thermal failure, topology optimisation can also be utilised to improve the cooling channels inside the piston. The cooling channels can be made more effective so that the piston can handle higher temperatures and pressures better engine performance as a result. Overall, piston topology optimisation is an effective tool for creating high-performance engines that adhere to the ever-stricter environmental and safety regulations. Manufacturers may achieve fuel efficiency criteria and still deliver the power and performance that customers want by developing lightweight and effective piston designs.

II. METHODOLOGY

A. CAD Modelling of the part

First step of all was to make a CAD model of the piston to be used in the project. The dimensions of the CAD model were acquired from a previous study. SOLIDWORKS was used to model the piston and make any further changes if required during the analysis. Figure 1 shows the CAD. The part in red is the non design space of the piston whereas the part in white is the design space.

B. Structural Analysis Of the Piston

At first the aluminium piston CAD is turned into STEP file for exporting to ANSYS. Again in ANSYS the material is assigned to the shell and core part for the piston. Then structural analysis is done onto the piston.

In our project the values for the engine force is taken from research papers given in the references. Then the first step was to add mesh to the component.

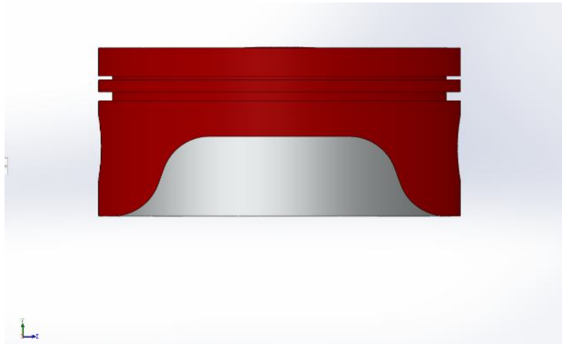

Figure 1 Side View of the Piston CAD

The process of breaking down a geometric domain or model into smaller, easier-to-understand subregions known as finite elements or mesh elements is known as meshing, also known as Meshing. Numerous numerical techniques used in engineering, physics, and mathematics, such as

finite element analysis (FEA), computational fluid dynamics (CFD), and molecular dynamics simulations, require meshing as a crucial step. By using a discrete set of elements to mimic a continuous domain or model, computational methods can be used to analyse and solve the problem numerically. Depending on the problem's dimensions, the mesh elements are frequently straightforward geometric shapes like triangles, quadrilaterals, tetrahedra, or hexahedra. Here in our project we went with tetrahedral mesh with mesh size 3 mm and used adaptive sizing.

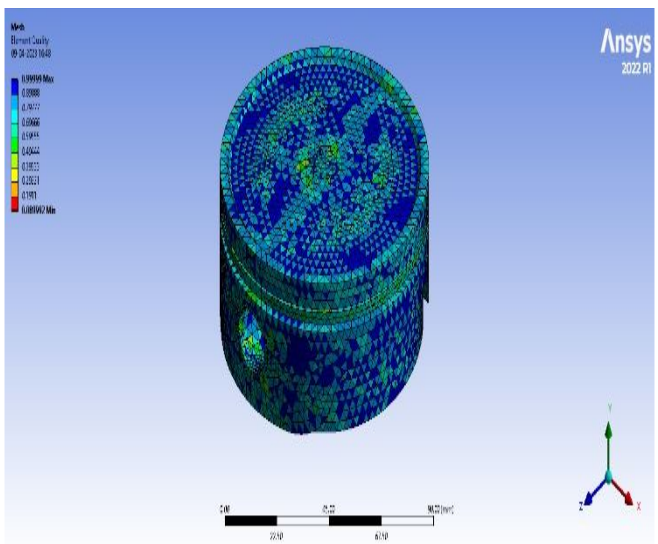

Figure 2 Mesh of the piston

The mesh transition is kept slow. The mesh has in total 96997 nodes and 58837 elements. Figure 3 shows the mesh of the piston. Then we added supports necessary which are the cylindrical support for the piston for the gudgeon pin side which was followed by application of the force the piston crown or the upper surface of piston where the combustion occurs and tremendous amount of force is exerted. The values of force were used as per the paper given in the reference. After applying all the boundary conditions Static Structural analysis was done and we got the equivalent or von misses stress results and also got the total deflection in the piston after application of force. Figure 4 shows the total deformation of the piston in true scale. The values acquired are of little importance to us as the initial CAD is already a proven design. Figure 5 shows stress distribution on the piston. The next module of topology optimization will use these values to optimize the part. This newly obtained information will be used by Ansys solver to find out what part of the piston is unnecessary.

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C. Topology Optimisaton Of Piston

Using the above structural analysis and transferring the data to the structural optimisation. After this step we need to add the optimisation region for the piston. In our case, the piston has the shell and the core part. So, the scope region for the topology optimisation was for core and the exclusion region was kept for the shell.

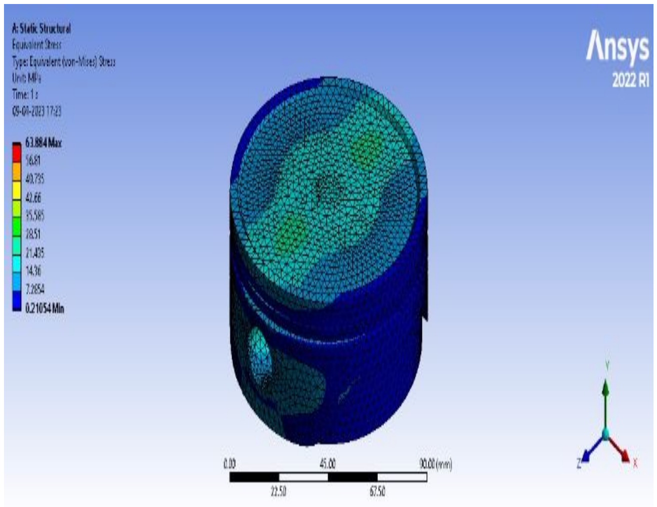

Figure 3 Equivalent Stress on the Piston

The topology optimisation-density based was selected. Density based method is not a new technology. It is also known as Solid Isotropic Material with Penalization(SIMP). The SIMP approach is founded on the idea of density. A design domain is discretized into small, finite components, and each element is given a density value—ranging from 0 to 1—that indicates how much material is present in that element on a relative basis. A density of 0 denotes the absence of all material, whereas a density of 1 denotes the presence of all material. In order to encourage the optimisation algorithm to converge towards a binary solution, where the density of each element is either 0 or 1, the SIMP technique employs a penalization function that penalises intermediate densities between 0 and 1. The level of penalization and smoothness of the final solution are regulated by a penalty factor, which can be used to adjust the penalization function.

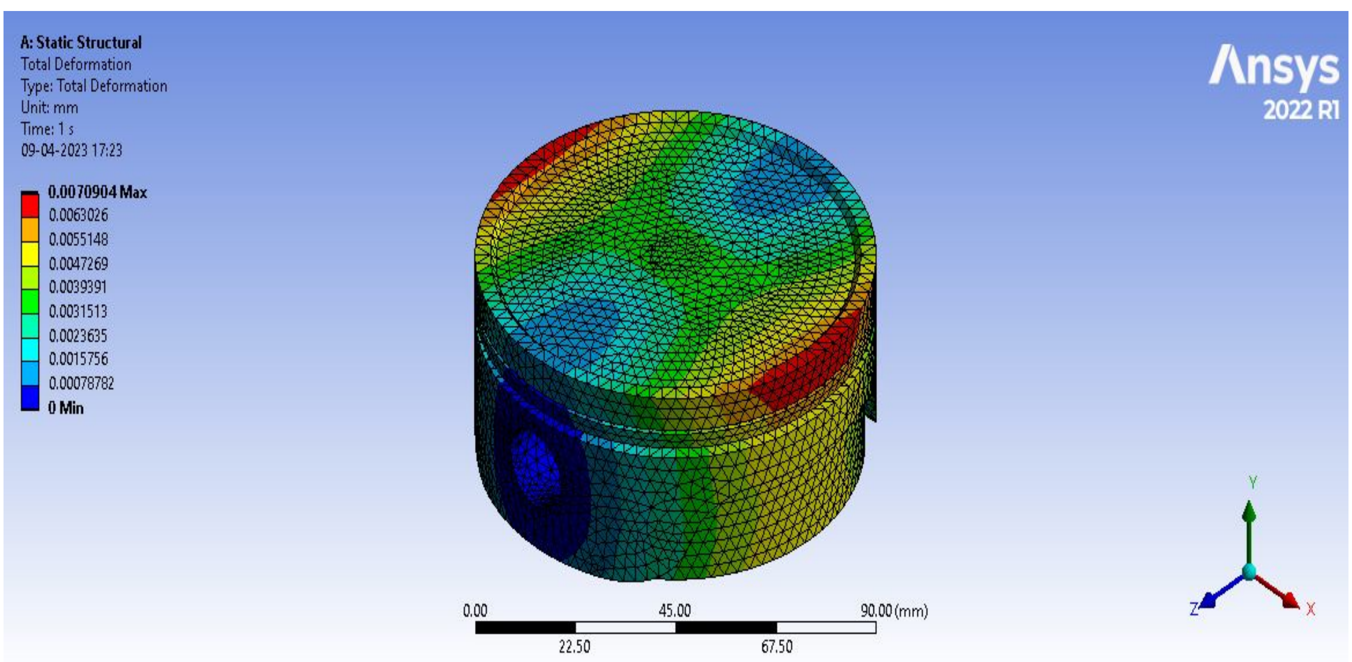

Figure 4 Deformation of the Piston (True Scale)

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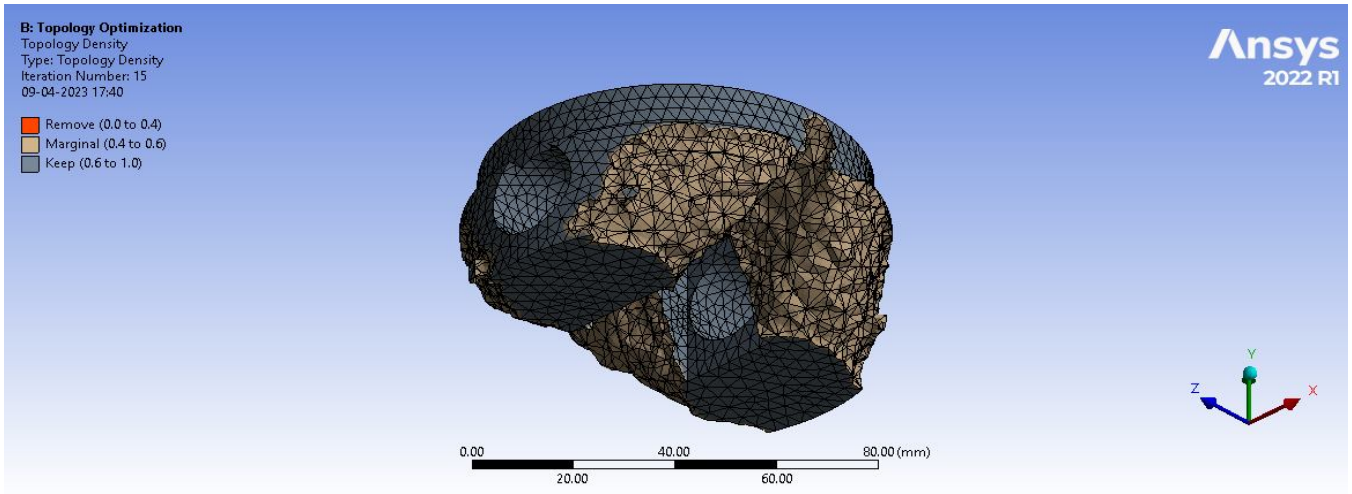

Figure 5 Results of Topology Optimisation

The goal of the mathematically described optimisation issue is to reduce the compliance of the structure under a given set of constraints, such as volume or stress limitations. The compliance is a measurement of the deformation or strain energy caused by loads or forces outside the structure. Then the response constraint is added like how much mass we need to retain. The convergence accuracy of the analysis was set to 0.1%. The amount of mass to be retained was set to 69%. After feeding all the parameters we performed the topology optimisation. The solution converged after 15 iterations. And we got the optimised model for our project. Figure 5 of the result of topology optimization

Areas where mass was reduced shown in brown colour. The results of this were then exported to a separate geometry module where it was further edited. As can be seen in the image above, the model is not very smooth. The lowest resolution of the model is basically the element size. So to make this manufacturable, the CAD was smoothened. Figure 6 shows the finalised CAD.

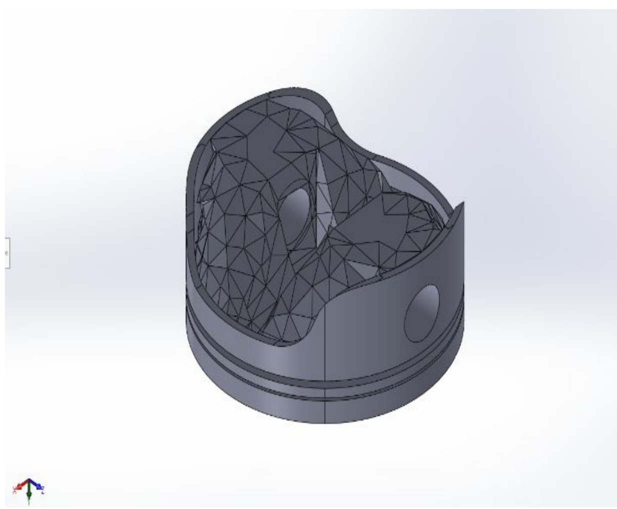

Figure 7 Final CAD

III. RESULTS

A. *Design Validation*

To validate the optimised part we performed the same structural analysis as given above because we need every aspect of the piston to be same as before. So the same steps were repeated and got these results given in the pictures. Figure 9 on the next page shows the workflow of the Ansys workbench project and further below in figure 10 are the results of static analysis.

Topology Optimisation Of Piston was completed successfully. Next step was to 3d print the model. The file was put through a 3d printing slicer software. Slicing Software used was Ultimaker Cura.

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Software	UltiMaker Cura
Material	PLA
Layer Thickness	250 Microns
Nozzle Diameter	0.4mm
Bed Temperature	60^{o}
Infill Density	10%
Top and Bottom walls	3

Figure 8 3d printed prototype of the piston

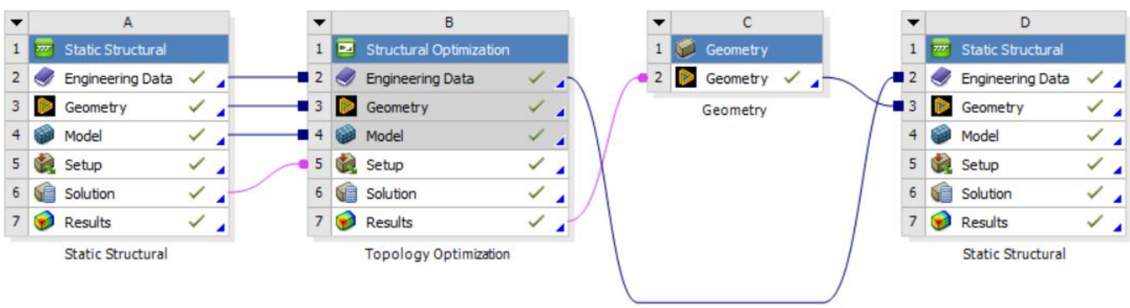

Figure 9 Ansys Workbench Flow

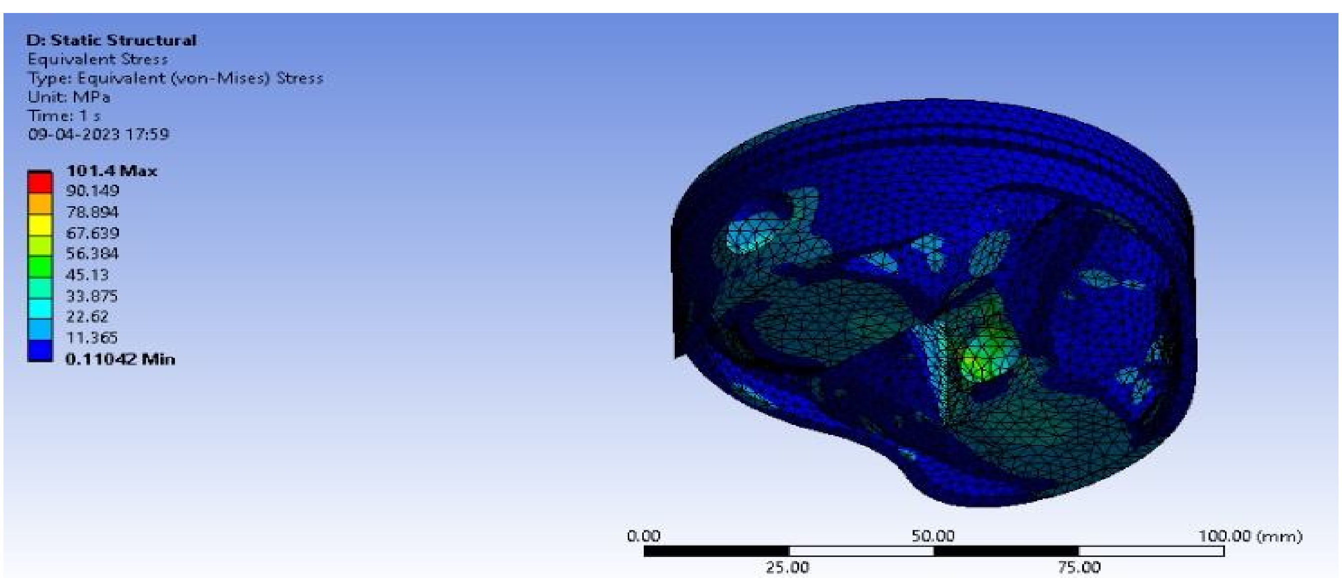

Figure 10 Results Of Design Validation (Stress Distribution)

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IV. CONCLUSION

Topology of the piston was optimized. Initial volume of the piston was 226830.49mm^3 whereas after optimization the volume was reduced to 167642.73mm^3. The material used for the piston was Aluminium Alloy. Thus a total weight reduction of 160gms was achieved. Initial weight was 614g whereas final weight was 454g.

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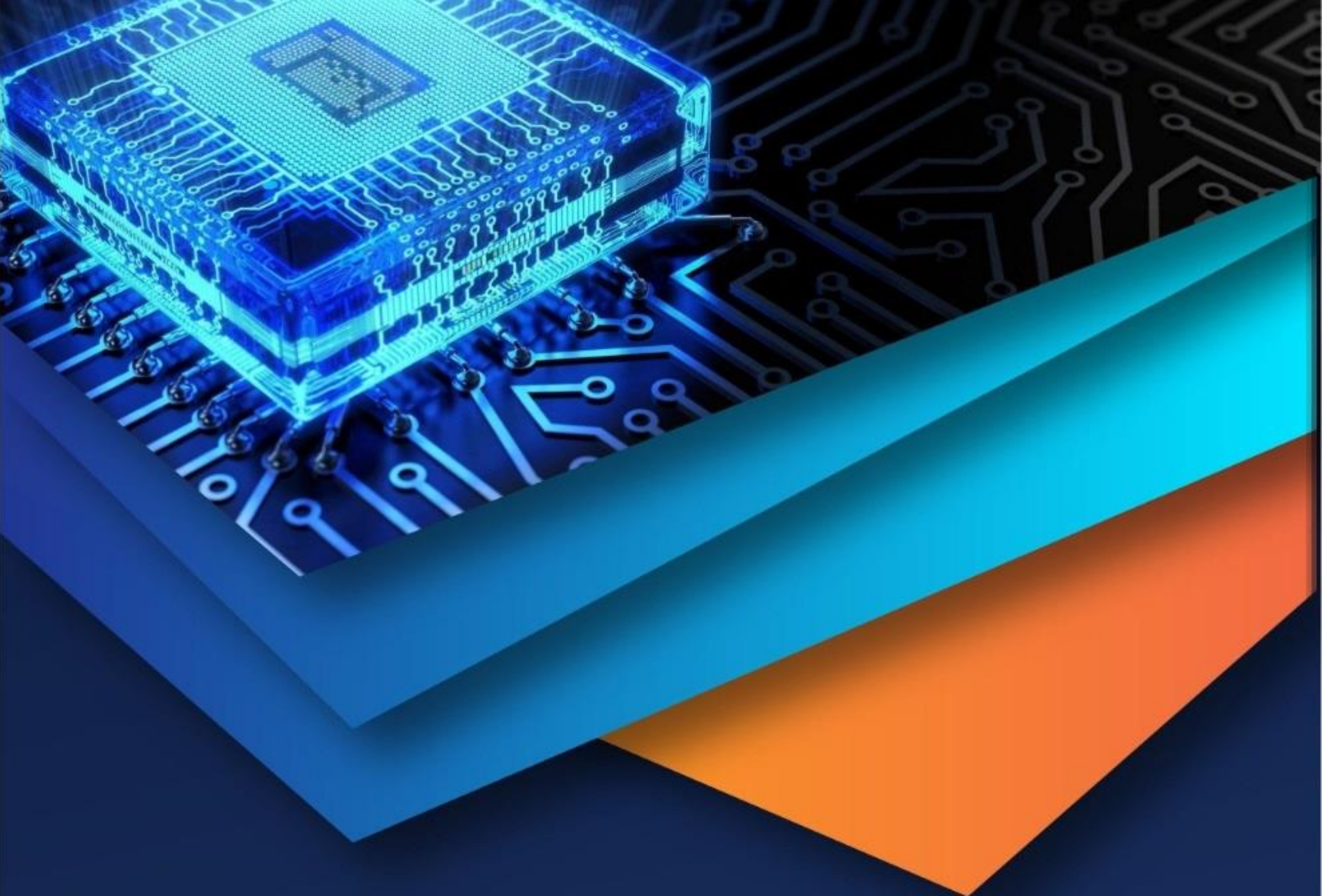

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