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Mechanical Behavior Analysis of Strut-Based Implant for Hip joint

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Abstract: Hip implants are crucial for the rehabilitation of injured or dislocated hip joint. Generally, solid implants made of metal alloys are used for orthopaedic applications. Solid implants are good for bearing loads but these are high in weight and less compatible with the natural bones. Porous hip implants are gaining importance due to its low weight and more compatibility with bones. Design of porous cells plays significant role in deciding and managing the strength, weight and biocompatibility issues. These porous issues are deal with designing lattice- based patient specific implants and suitable for manufacturing using additive manufacturing technology. Present research work has been focused on design and analysis of strut-based diamond lattice-based hip implant using nToplogy software. Various biocompatible materials have considered for design and analysis.
Keywords: Hip Implant, Diamond lattice, FEA, Inconel 718, stainless steel 318, Ti-6Al-4V.

I. INTRODUCTION

The numerous joints in the human body are useful for daily activities. Each joint's mechanics and function are unique. Ball and socket joints are used in joints like the hip and shoulder. The head of the femur and the acetabulum of the pelvic bone articulate synovial at the hip joint.[1] The ball and socket joint are an assembly made up of the femoral head and the pelvic acetabulum. This joint occasionally became dislocated or distorted as a result of ageing and certain unintentional issues. Joint injury is also caused by some types of arthritis, including traumatic arthritis, rheumatoid arthritis, and osteoarthritis. As a result, the patient experiences discomfort and agony in the pelvic region when walking, climbing, and performing other daily activities due to the injured joint. Figure 1. shows basic anatomy of a hip joint. [1,2]

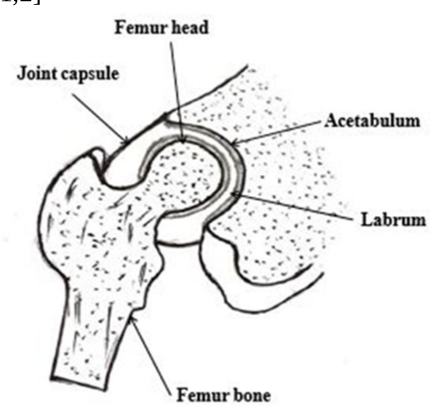

Fig. 1 Anatomy of hip joint

In several actions including jumping, walking, and running, the femur is the major load-bearing bone that carries the entire body weight.[3] A very serious and frequent occurrence, hip injuries can be fatal or leave victims permanently disabled.

Many patients cannot perform his daily life activities due to hip joint disease. hence hip surgery has common procedure. In hip replacement surgery diseased hip joint is replaced by an artificial joint, that is called prosthesis or Implant. Function of this prosthesis is transferring the load from acetabulum to femur with the help of metal stem. Stem is inserted in femur and it should be always remained contact with femur cortical bone to provide the fixation and stability of total hip replacement (THR) joint. This surgery procedure is used when no other option remains for treatment. The aim of this surgery to remove pain and improve mobility.[4]

The design and composition of hip implants have progressed consistently. The most difficult problems in implant technology's century-long progress can be found there.

To find the best material that could have properties like bone or a combination of biocompatibility and fatigue resistance, stiffness, and toughness so that it could wear static and dynamic loads, mechanical and chemical wear, a variety of materials and designs, including glass, polymer, metals, metal alloys, ceramics, and composites, were used. The first unsuccessful hip operations were place in England in 1750. Prof. Themistocles Gluck inserted an ivory ball and socket prosthesis that was screwed to the bone for the first time in 1880.[5]

In order to remove a femoral head in 1919, Delbet utilised rubber; in order to replicate the articular surface of the femoral head in 1922, Hey-Groves used an ivory nail. Marius Smith-Petersen presented the first femoral cup made of glass and Bakelite. Austin Moore introduced hemiarthroplasty, a novel implant, in 1950. Researchers are still working to develop novel materials and designs that will solve issues with hip prosthesis like stress shielding and implant loosening brought on by the different characteristics of bone and material.[5,6]

A number of factors cause about 10% of hip implant procedures to fail. bone diffusion with implant stem or ball displacement in liner. As a result of individual differences in joint size and shape, the ball might occasionally fall out of the cup area. To address this issue, personalised hip implants are created.[7]

Several hip joint-related geometrical parameters that have a direct impact on the precision of the resultant patient-specific implant shape. An essential factor is the implant's material choice. The first consideration is the material's strength in order for it to support the body weight. It should also be flexible because joints move. Additionally, the material should be biocompatible.

Currently, researchers are concentrating on hollow or light stems that may readily fuse with femur bones. Nowadays, strut-based lattice structures are frequently used to achieve hollow implants that are light and strong. There are numerous nodes in a diamond, octet, or kelvin lattice structure that connect to other unit cells and make it simple to transmit load. These lattice structures have a pattern similar to a bone structure and are appropriate for ortho implants. The stress shielding issue is also reduced by lattice structure-based Implants.[8]

The truss-based approach is advantageous for biomechanical applications like tissue scaffolds and implants. This technique involves replacing the solid section or a portion of it depending on the needs and integrating lattice structures, which makes the implant porous, light, and potentially ideal for bone formation. It also permits the diffusion of oxygen and nutrients.[10,11]

Lattice structures are classified in three categories, such as Strut based, TPMS based and Sheet TPMS based shown in figure 2. Strut based or beam based structure are preferable for lightweight, excellent damage tolerance and energy absorption. TPMS unit cell are favourable for structures with large surface area, high stiffness, and excellent manufacturability. Sheet TPMS are preferable for planar lattice structures or rib grids with the highest directional stiffness. These three types of structure have some more classification which is shown in figure 3.[12,13]

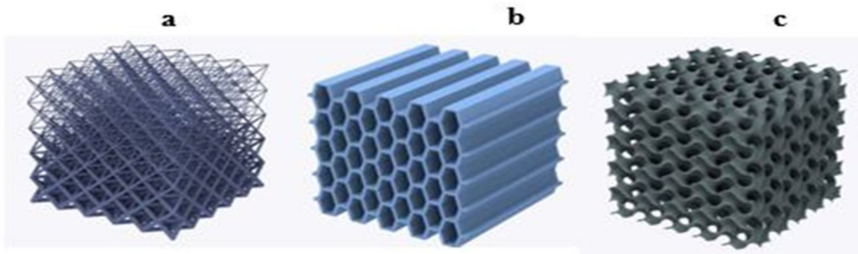

Fig 2. (a) strut, (b) Sheet TPMS, (c) TPMS

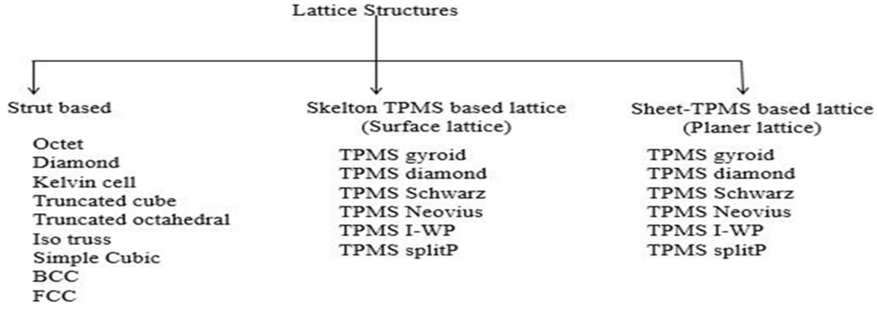

Fig 3. Classification of lattice structure[13]

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In this study, diamond lattice-based hip implant considered for biocompatible materials titanium alloy (Ti-6Al-4V), Inconal718, Stainless Steel 316. Unit cell of diamond lattice shown in figure 4.

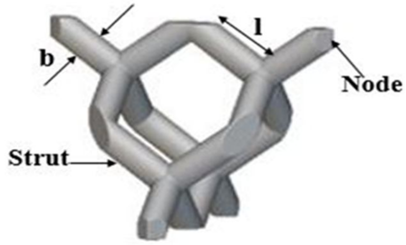

Fig 4. Diamond unit cell

II. METHODOLOGY

A. Modelling

The Solidworks modelling programme is used to create the lattice design for the hip joint implant. Stem measurements are taken based on earlier study articles. Critical dimensions ranges are indicated in Table 1. The Implant is essentially made of three pieces for simple lattice structure integration. There are currently rough-coated Implants are available in the market, allowing for bone integration and a reduction in the effect of loosening.

Table I
design parameter of hip Implant[10]

Design Parameters	Typical values
Length of intramedullary stem	120 mm - 180 mm
Length of neck	10 mm - 40 mm
Head diameter	22 mm - 45 mm
Neck diameter	13 mm - 30 mm
Angle of head placement	135^0-145^0

Solid Implant designed in Solidworks with dimensions shown in figure 5. (a) and diamond lattice-based implant shown in figure 5. (b)

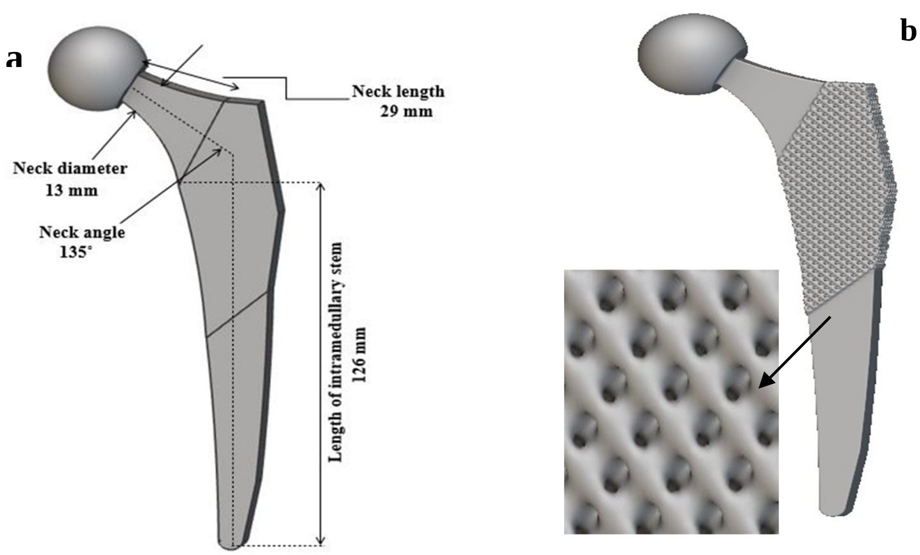

Fig 5. (a) Solid Implant, (b) diamond based solid lattice Implant

Solid parts import in n topology middle part of implant converted into lattice part by using cell map option and the all part combined by using Boolean option. Beam thickness of lattice is taken 1.2. figure 5(b) showing the modelled hip stem.

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B. Analysis

Implant is analysed under static loading condition; 2300 N load is applied on the face of stem head and bottom part of the stem considered as a fixed part. Load face and fixed condition are taken according to previous studies. Figure 6. is showing the all conditions.

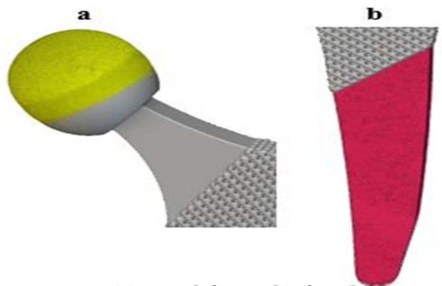

Fig 6. (a) Load face, (b) fixed faces

Titanium alloy (Ti-6Al-4V), Steal 316, Inconel 718 are material taken for study of mechanical behaviour of implant, these are biocompatible material and titanium alloy is favourable material. Material properties are presented in table 2.

Table II
Material properties

Mechanical Properties	Cancellous Bone	Cortical Bone	Inconel 718	Stainless steel 316	Titanium alloy
Density	0.03-0.12 g/cm3	1.6-2.0 g/cm3	8.2 g/cm3	8 g/cm3	4.51 g/cm3
Elastic Modulus	0.05-0.5 GPa	12-20 GPa	210 GPa	193 GPa	114 GPa
Poisson Ration	0.3	0.3	0.29	0.27	0.3
Yield Strength	na	113 MPa	1200 MPa	205 MPa	880 MPa
Tensile strength	10-20 MPa	146 MPa	1375 MPa	480 MPa	897 MPa
Compressive strength	2-16 MPa	130-200 MPa	1700 MPa	320 MPa	848 MPa

III. RESULTS AND DISCUSSIONS

The behaviour of various possible biocompatible materials is modelled and examined for a hip implant made of diamond lattice. Inconel 718, stainless steel 316, and titanium alloy. Table 5 presents the von-Misses stress and displacement. Researchers suggested a new, sophisticated material in the previous decade, specifically for orthopaedic implants, which were also subjected to research. Inconel 718 is that. The entire implant is made of tetrahedral mesh, with edge length 1 being used. Figure 7 displays the deformation as a result, and Figure 8 displays the von-Mises stress of different materials under load. Maximum stress shown in the table 5 are compressive and reached to its higher value, these stress occur only in a specific point and did not shows the total Mechanical behaviour of the implant. Rest stress lies in the range, for solid implant (64MPa-129MPa), for lattice based Ti-6Al-4V implant (52MPa-105MPa), for Inconel 718 (55MPa-111MPa), for Stainless steel 316 (56MPa-112MPa).

Table III
Analysis results

Structure		Material		
		Inconel 718	Stainless steel 316	Titanium alloy
Solid	Stress (MPa)	611.95	613.96	582.60
	Displacement (mm)	0.0526	0.05870	0.09897
Diamond	Stress (MPa)	502.84	504.96	474.98
	Displacement (mm)	0.06468	0.06468	0.01468

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Solid Implant have more volume than diamond lattice based solid Implant volume. Due to porosity implant become lightweight also. For hip Implants porosity reduce the stress shielding but some how increase in porosity reduce the strength of implant. Volume of both implant and porosity% shown in Table 6.

$$\text{Porosity\%} = 1\text{-}\frac{\textit{porous implant volume}}{\textit{solid implant volume}}\text{x}100$$

Table IV
Porosity and mass result

Implant Type	Volume (mm3)	Porosity (%)	Mass (g)	Mass Reduced (g)
Solid	46817.48	5.9%	211.1463	13
Porous	44049.35		198.6626	

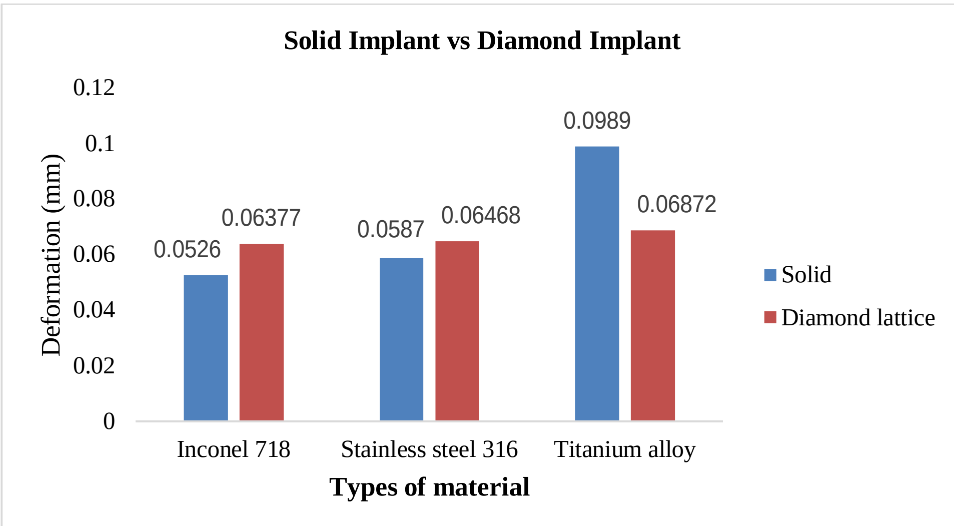

Fig 7. Deformation of both solid and lattice Implant

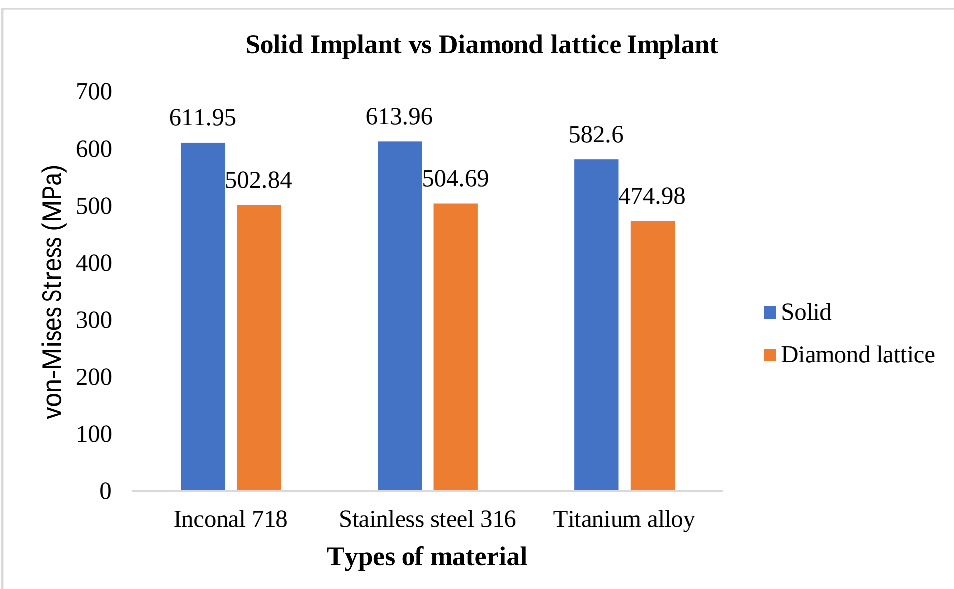

Fig 8. von-Mises stress of solid and lattice Implant

IV. CONCLUSIONS

In this study two most common material and one last decade developed material, especially for orthopaedic implant taken for study of mechanical behaviour of lattice-based implant. Diamond based lattice implant are suggested by researcher. Node connectivity of Diamond lattice makes it structurally efficient. Solid implant of material Ti-6Al-4V has von-Misses stress lower than the material yield strength but slightly upper the range of cortical bone yield strength. In comparison to diamond based lattice implant range of von-Misses stress decrease and below the range of cortical bone yield strength and material yield strength. This reduced the chance of failure of implant. Similarly with Inconel 718 material shows good Mechanical behaviour as Ti-6Al-4V so it would be substitute of it in future. But in case of stainless steel 316 its stress range is close to material yield strength so the life of this type of implant reduced. Reduction of mass also decreases the required construction material.

Porosity behaviour allows bone growth, tissue regeneration through diffusion of cell, oxygen and other nutrients in implant, porosity can be decreased and increased by changing the unit cell size, volume, number. Inconel 718 material shows good result like most preferable material titanium alloy (Ti-6Al-4V). In future by changing cell size, number, and strut thickness of the lattice mechanical behaviour of implant can be studied.

V. ACKNOWLEDGMENT

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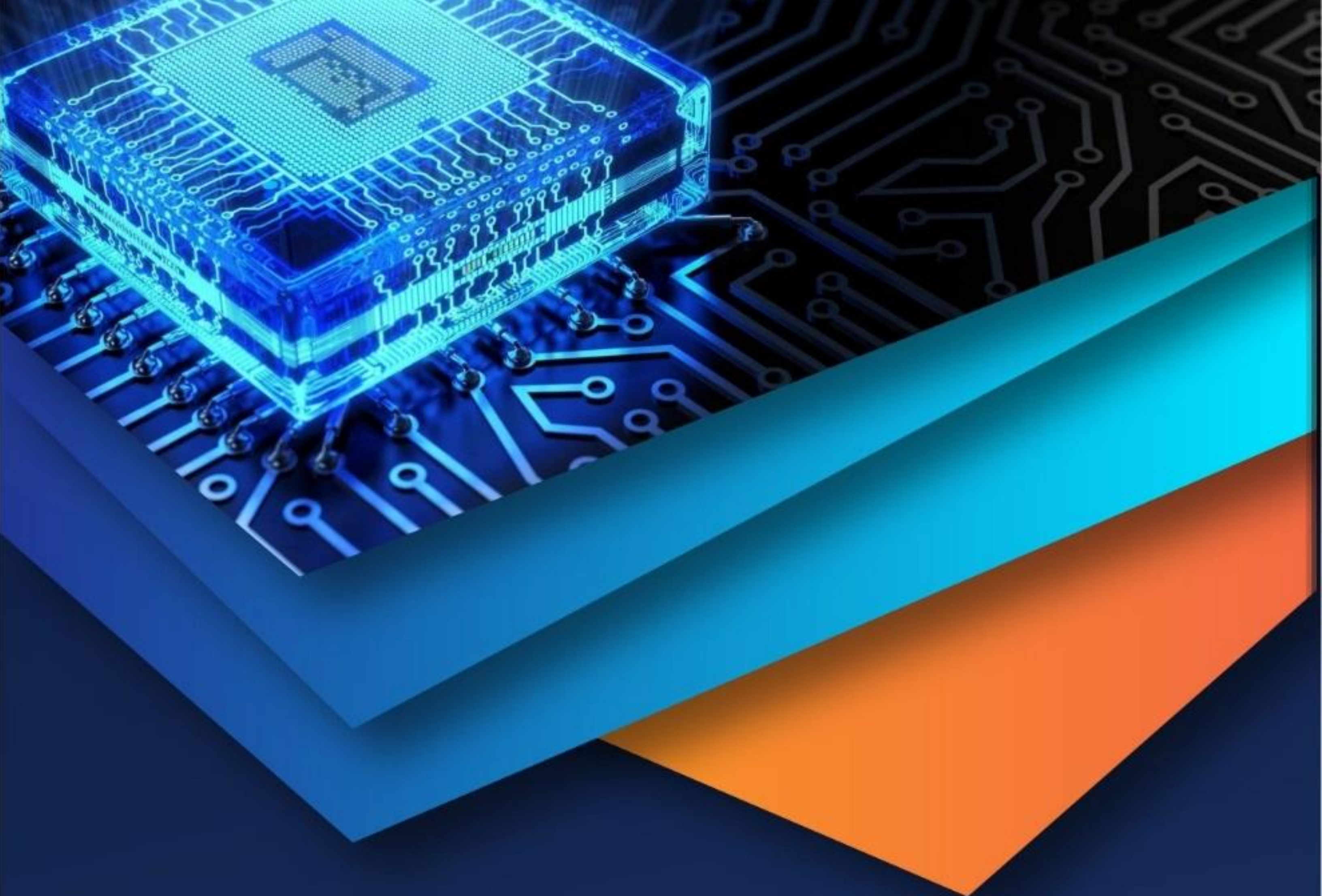

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