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Finite Element Analysis of Hip Prosthesis with Neck Fracture under Various Human Activities

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***Abstract*: The functioning of the normal and defective artificial hip joint during various movements has been studied with the help of finite element analysis. The movements selected for this analysis were flexion, extension, abduction and adduction. These are the basic movements for a hip joint combination of which results to various day to day activities. These movements have been analyzed for both defective and non defective artificial hip joints. Three different materials namely titanium alloy, cobalt chromium alloy and stainless steel are used for the study. A 3D modeling software, meshing software and finite element analysis software have been used in this study. The obtained results from the analysis have been evaluated and the stresses and deflections were compared with the acceptable values of the respective materials. The stresses exceeding the yield strength have been concluded to result in fracture. The conclusions made helped in determining the possibility of failure of the artificial hip joint and hence avoid secondary hip replacement**.

***Index Terms*: Artificial Hip Joint (Hip Prosthesis), Finite Element Analysis, Revision Hip Surgery, Total Hip Replacement, Total Hip Arthroplasty.**

I. INTRODUCTION

The hip joint, scientifically referred to as the acetabular femoral joint, is the joint between the femur and acetabulum of the pelvis. The primary function of the joint is to support the weight of the body in both static (standing) and dynamic (walking or running) postures. The hip joints play a very important role in retaining the balance of the body. In mechanical terms hip joint is a ball and socket joint [1-3]. Total Hip Arthroplasty (THA) is a surgery carried to replace the defective natural hip joint with artificial hip joint and the first surgery performed is called primary hip replacement surgery. An artificial hip is a kind of prosthesis that typically consists of two or more components. It usually has a stem which fits into the femur, a ball fitted to the top of the stem, and a cup which is fitted into the acetabulum and which provides a smooth sliding surface for the ball [4-7]. After few years of primary THA there is increasing need for secondary THA due to the failure of artificial hip joints. It is also evident from various registries of hip surgeries that in India this trend is increasing. The reason for artificial hip joint failure may be internal body forces or external forces due to various day to day to human activities or may be dependent on the properties of the artificial hip joint material [8-10]. So after primary THA there is a need for monitoring the artificial hip and analyze the causes of the failure of the artificial hip joint to avoid secondary surgery. Asceptic loosening, infection, periprosthetic fracture, dislocation, component failure due to crack are some of the causes of the artificial hip joint after primary THA. In this study we have taken crack as a reason for failure for artificial hip joint which leads to fracture.

II. METHODOLOGY

Due to the vast number of reasons leading to the failure of artificial hip joint, only specific common factor were selected for the stress analysis pertaining to our study. The stress analysis of the prosthesis is done using suitable finite element analysis software. Based on the literature review Titanium alloy (Ti-6Al-4V), Cobalt - Chromium alloy (CoCr) alloy and Stainless steel alloys have been selected for the analysis [4-10]. Fracture in the femoral neck of the artificial hip joint is chosen as the defect for analysis. The analysis of the hip joint is carried out in its static position for the movements namely adduction, abduction, flexion and extension. The 3D modeling of the normal and cracked artificial hip joint is done in the advanced modeling software and imported in the meshing software in .igs format. After meshing, boundary conditions and loads are applied on the elements and imported the elements in analysis software for solution and post processing. The stress values and deformation values for all the three materials and various movements are compared and arrived at the conclusion. The dimensions selected for the hip prosthesis 3D modeling in this study is that of an adult male having a body weight (BW) of 750N. Figure 1 is the meshed model of the artificial hip joint showing internal elements.

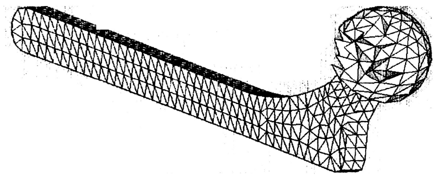

Figure 1: Meshed model showing internal elements

III. MATERIALS AND LOADS

Metal on Metal (MOM) hip prosthesis is most efficient and commonly used. In MOM hip prosthesis both the stem and the acetabular cup are made up of metals or alloys. The materials used for the cup and stem may be the same or different. In our study same material for both the components are considered. The materials compared are Titanium Alloy (Ti-6Al-4V), Cobalt Chromium Alloy (CoCr) and Stainless Steel alloy. Ti-6Al-4V is light in weight, has extraordinary corrosion resistance and the ability to withstand extreme temperatures. Titanium alone is a strong, light metal. It is stronger than common, low carbon steels, but 45% lighter. It is also twice as strong as weak aluminium alloys but only 60% heavier. Since titanium does not react within the human body, it and its alloys have been very popular in the field of medical sciences. They are used to create artificial hips, pins for setting bones and for other biological implants. For most medical applications titanium is alloyed with small amounts of aluminum and vanadium, typically 6% and 4% respectively, by weight. CoCr is used in various fields where high wear resistance is needed. This alloy is widely used for the manufacture of many artificial joints including hips and knees, dental partial bridge work, etc. The stainless steel alloy with a minimum of 10.5% chromium content by mass does not corrode, rust or stain with any of the body fluids.

A. Loads for Single Legged Stance

The hip joint reaction force F_J generated during single legged stance is a function of body weight W. For the Single Legged Stance (SLS) [1-10] using the notations given in Figure 2 we have $W_2 = \frac{5}{6} \times W$, $a = 50\,mm, c = 130\,mm$ and $\theta = 70^0$.

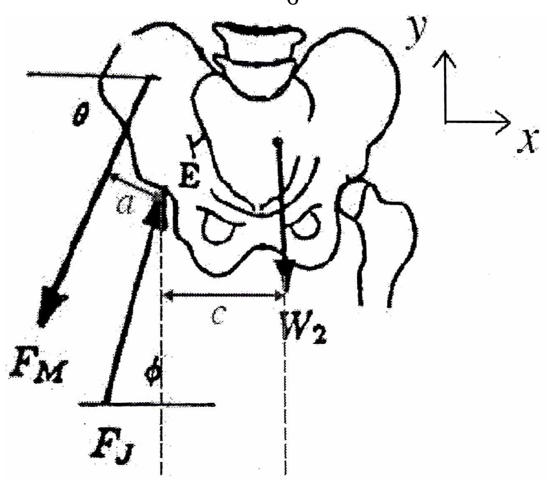

Figure 2: Free body diagram of forces acting during SLS

Considering equilibrium condition we have $\sum F_x = 0$, $\sum F_y = 0$ and $\sum M_E = 0$.

On resolving the forces, we get

$$\sum F_x = F_J \cos\phi - F_M \cos\theta = 0 \qquad (1)$$

$$\sum F_y = F_J \sin\phi - (F_M \sin\theta + W_2) = 0 \qquad (2)$$

On taking moments about point E, we get

$$\sum M_E = (F_M \times a) - (W_2 \times c) = 0$$

$$F_M = W_2 \times \left(\frac{c}{a}\right)$$

On substituting $W_2 = \frac{5}{6} \times W$ for SLS, we get

$$F_M = \left(\frac{5}{6} \times W\right) \times \left(\frac{c}{a}\right)$$

On substituting $a = 50\,mm$ and $c = 130\,mm$ for SLS, we get

$$F_M = \left(\frac{5}{6} \times W\right) \times \left(\frac{130}{50}\right)$$

$$F_M = 2.17W \qquad (3)$$

From equation (1), we get

$$F_J = F_M \left(\frac{\cos\theta}{\cos\phi}\right)$$

On substituting $\theta = 70^0$ for SLS and using equation (3),

$$F_J = \frac{(2.17 \times W) \times \cos 70^0}{\cos\phi} \qquad (4)$$

From equation (2), we get

$$F_J = \frac{(F_M \sin\theta + W_2)}{\sin\phi}$$

On substituting $W_2 = \frac{5}{6} \times W$ for SLS, we get

$$F_J = \frac{\left[F_M \sin\theta + \left(\frac{5}{6} \times W\right)\right]}{\sin\phi}$$

On substituting $\theta = 70^0$ for SLS and using equation (3),

$$F_J = \frac{\left\{\left[(2.17 \times W) \times \sin 70^0\right] + \left(\frac{5}{6} \times W\right)\right\}}{\sin\phi} \qquad (5)$$

Equating equations (4) and (5), we get

$$\frac{\sin\phi}{\cos\phi} = \frac{\left\{\left[(2.17 \times W) \times \sin 70^0\right] + \left(\frac{5}{6} \times W\right)\right\}}{(2.17 \times W) \times \cos 70^0}$$

$$\tan\phi = \frac{\left[\left(2.17 \times \sin 70^0\right) + \left(\frac{5}{6}\right)\right]}{\left(2.17 \times \cos 70^0\right)}$$

$$\phi = \tan^{-1}\left\{\frac{\left[\left(2.17 \times \sin 70^0\right) + \left(\frac{5}{6}\right)\right]}{\left(2.17 \times \cos 70^0\right)}\right\}$$

On simplification, we get $\phi = 75.5^0$

From equation (4), we have

$$F_J = \frac{(2.17 \times W) \times \cos 70^0}{\cos 75.5^0}$$

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$$F_J = 2.96W \quad (6)$$

In this study an adult male having a body weight (BW) of $W = 750\,N$. On substituting for W in equation (3) and (6), we get $F_M = 1627.5N$ and $F_J = 2220\,N$. These loads along with the boundary conditions have been applied on the prosthesis for the analysis of SLS.

B. Loads for Various Motions

Figure 3 shows the hip joint and the involved muscle forces for the movements namely flexion, extension, abduction and adduction [1-10]. The Figure 2 gives the point and angle of application of hip joint force at point A, adductor muscle force at point C and abductor muscle force at E. The magnitude of forces is given by 4.9W at point A, 0.65W at point C and 1.79W at point E. Considering an adult male having a body weight (BW) of $W = 750\,N$, we get a force value of 3675N at point A, 487.5N at point C and 1342.5N at point E.

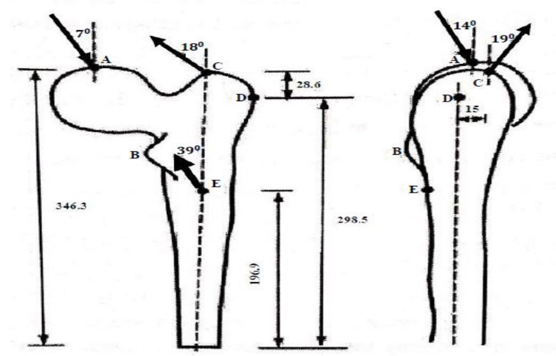

Figure 3: Posterior and Lateral View of forces acting on hip joint during the motions (All dimensions are in mm)

Applying loads on the precise locations is necessary to get the optimum results. After a thorough research of various literatures the following boundary conditions have been used for the analysis. The forces acting on the hip joint may include the forces acting from the center of gravity of the body, at the contact of the acetabular cup and the femoral head and also muscle forces. The major force is the body weight. The stem portion of the joint is fixed as it is placed inside the femur. The stem of the hip joint is fixed. A total of three forces are considered to be acting on the artificial hip joint. The force due to contact between the cup and the ball is also applied. All the muscle forces acting are applied as one resultant force. Vertically downward force is applied on the center of the gravity. On an average the center of gravity of human body lies at about 130mm inwards from the femoral head.

IV. RESULTS AND DISCUSSION

This section gives the tabulation of the results obtained from the finite element analysis of the selected movements and materials. It also includes the comparison of the stresses with their respective Yield strength to determine the possibility of failure of the hip prosthesis. The Yield Strength of Ti-6Al-4V, CoCr and Stainless Steel is 880MPa, 819MPa and 520MPa respectively. Table 1 gives the comparison results obtained for the Single Legged Stance (SLS) loading conditions for the normal and defected hip prosthesis. Table 2 and 3 gives the comparison of results for the normal and defective hip prosthesis for abduction respectively.

Table 1: Comparison of results obtained for SLS

Materials	Normal		Defective	
	Stress (MPa)	Deflection (mm)	Stress (MPa)	Deflection (mm)
Ti-6Al-4V	208.27	0.27492	894.04	0.27866
CoCr	277.43	0.14305	897.07	0.145
Steel	276.86	0.15527	898.32	0.15738

Table 2: Comparison of results of normal hip for Abduction

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4 V	2	499.27	0.67477
	5	514.23	0.64654
	7	514.23	0.62870
	10	494.07	0.61360
	12	493.31	0.59100
	15	489.82	0.57247
CoCr	2	502.71	0.35242
	5	516.05	0.33757
	7	514.16	0.32821
	10	498.01	0.31567
	12	488.34	0.30823
	15	494.12	0.29846
Stainless Steel	2	503.35	0.38280
	5	516.52	0.36663
	7	514.72	0.35645
	10	499.04	0.34281
	12	487.14	0.33468
	15	495.24	0.32404

Table 3: Comparison of results of defective hip for Abduction

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4 V	2	499.32	0.70116
	5	525.33	067697
	7	564.52	0.66364
	10	630.05	0.64754
	12	692.46	0.63853
	15	756.87	0.62977
CoCr	2	501.16	0.36624
	5	531.29	0.35356
	7	571.27	0.34657
	10	637.64	0.33803
	12	698.27	0.33328
	15	765.52	0.32858
Stainless Steel	2	502.60	0.39783
	5	533.23	0.38406
	7	573.26	0.37645
	10	639.80	0.36714
	12	700.09	0.36194
	15	764.28	0.35684

Table 4 and 5 gives the comparison of results for the normal and defective hip prosthesis for adduction respectively.

Table 4: Comparison of results of normal hip for Adduction

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4 V	2	496.74	0.71828
	5	506.62	0.75580
	7	484.92	0.78274
	10	489.39	0.82686
	12	515.01	0.85932
	15	485.18	0.91054
CoCr	2	500.15	0.37523
	5	509.83	0.39495
	7	486.90	0.40892
	10	490.97	0.43205
	12	517.07	0.44895
	15	486.07	0.47567
Stainless Steel	2	500.99	0.40760
	5	510.61	0.42906
	7	487.35	0.44420
	10	491.33	0.46935
	12	517.55	0.48769
	15	486.55	0.51671

Table 5: Comparison of results of defective hip for Adduction

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4 V	2	509.54	0.73993
	5	509.32	0.77543
	7	505.58	0.80281
	10	530.75	0.84757
	12	517.13	0.88085
	15	507.71	0.93352
CoCr	2	510.71	0.38677
	5	510.46	0.40534
	7	506.90	0.41952
	10	532.58	0.44281
	12	518.92	0.46016
	15	508.87	0.48771
Stainless Steel	2	511.32	0.42020
	5	510.72	0.44038
	7	507.21	0.45575
	10	533.03	0.48102
	12	519.35	0.49986
	15	509.14	0.52979

Table 6 and 7 gives the comparison of results for the normal and defective hip prosthesis for flexion respectively.

Table 6: Comparison of results of normal hip for Flexion

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4V	5	535.75	0.72427
	10	570.80	0.83273
	15	603.35	0.93435
	20	646.77	1.03330
	25	657.52	1.12530
	30	674.30	1.2093
	35	687.09	1.2846
	40	695.62	1.3507
CoCr	5	537.52	0.37892
	10	572.47	0.43551
	15	604.77	0.48903
	20	650.06	0.54057
	25	658.45	0.58882
	30	674.88	0.63277
	35	687.88	0.67226
	40	696.46	0.70687
Stainless Steel	5	537.93	0.41177
	10	572.82	0.47323
	15	605.07	0.53147
	20	650.81	0.58742
	25	658.60	0.63989
	30	674.94	0.68764
	35	687.47	0.73059
	40	696.60	0.76820

Table 7: Comparison of results of defective hip for Flexion

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4V	5	427.447	0.29266
	10	642.82	0.46778
	15	761.28	0.38735
	20	895.27	0.31402
	25	1007.2	0.33165
	30	1100.4	0.41159
	35	1199.00	0.52341
	40	1321.7	0.64841
CoCr	5	428.82	0.15088
	10	647.52	0.24407
	15	766.30	0.19136
	20	897.19	0.16327
	25	1011.4	0.17243
	30	1204.0	0.21427
	35	1140.8	0.27286
	40	1326.20	0.33830
Stainless Steel	5	429.181	0.16321
	10	649.070	0.26506
	15	767.930	0.20774
	20	898.110	0.17717
	25	1012.90	0.18710
	30	1106.30	0.23257
	35	1205.60	0.29626
	40	1327.80	0.36737

Table 8 and 9 gives the comparison of results for the normal and defective hip prosthesis for extension respectively.

Table 8: Comparison of results of normal hip for Extension

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4V	5	444.99	0.510
	10	415.37	0.40999
	15	367.78	0.32964
	20	314.53	0.28715
	25	355.86	0.30083
	30	396.06	0.3645
CoCr	5	446.95	0.26643
	10	411.35	0.21404
	15	364.66	0.17177
	20	311.56	0.14937
	25	352.66	0.15649
	30	392.49	0.18994
Stainless Steel	5	447.43	0.28944
	10	410.39	0.23249
	15	363.91	0.18649
	20	310.82	0.16211
	25	351.87	0.16984
	30	391.60	0.20621

Table 7: Comparison of results of defective hip for Extension

Material	Angles (Degrees)	Max. Stress (MPa)	Deflection (mm)
Ti-6Al-4V	5	595.34	0.9959
	10	581.09	0.9405
	15	622.01	1.1049
	20	573.69	0.85936
	25	595.45	0.8804
	30	603.98	0.91345
CoCr	5	501.49	0.44921
	10	487.46	0.47859
	15	622.86	0.57756
	20	457.36	0.40963
	25	561.94	0.40394
	30	595.89	0.39405
Stainless Steel	5	557.38	0.58924
	10	534.92	0.52305
	15	623.02	0.62748
	20	479.03	0.50134
	25	499.03	0.55093
	30	510.93	0.59034

From Table 2 and 3 it can be observed that the maximum stress of the stainless steel model with defect exceeded the yield strength while the other materials were able to withstand the load of abduction. From Table 4 and 5 it can observed that none of the stresses of the models exceed the yield strength for adduction. Hence for adduction, materials with lower yield strength can be used irrespective of the position of the prosthesis without any risk of fracture.

From Table 6 and 7 it can be observed that the maximum stresses of all three materials with defect exceeded their respective yield strength at 40^0 from the body line. Thus the flexion of the prosthesis is limited to angles less than 40^0 to avoid failure due to fracture.

From Table 8 and 9 it can be observed that the maximum stress of only the stainless steel model with defect exceeded the yield strength while the other materials were able to withstand the load. Hence for extension, materials other than stainless steel can be used irrespective of the position of the prosthesis without any risk of fracture.

V. CONCLUSION

From the results it can be concluded that this study has been able analyze the failure of artificial hip joint for particular materials at certain positions. Stainless steel failed in three of the four movements proving that it is not suitable for use in the manufacture of hip prosthesis. The defective hip joint composed of Cobalt Chromium Alloy withstood loads in all movements except for flexion at 40^0. The defective hip joint composed of Titanium alloy withstood loads in all movements except for flexion at 40^0. Out of the two alloys Titanium alloy could be considered for better use due to its higher yield strength and durability compared to Cobalt Chromium Alloy. The movements of the hip joint at extreme position could result in failure irrespective of the material used. Hence, the subject is advised to use hip prosthesis composed of Titanium Alloy and avoid extreme movements of the leg to keep the secondary THA at the bay.

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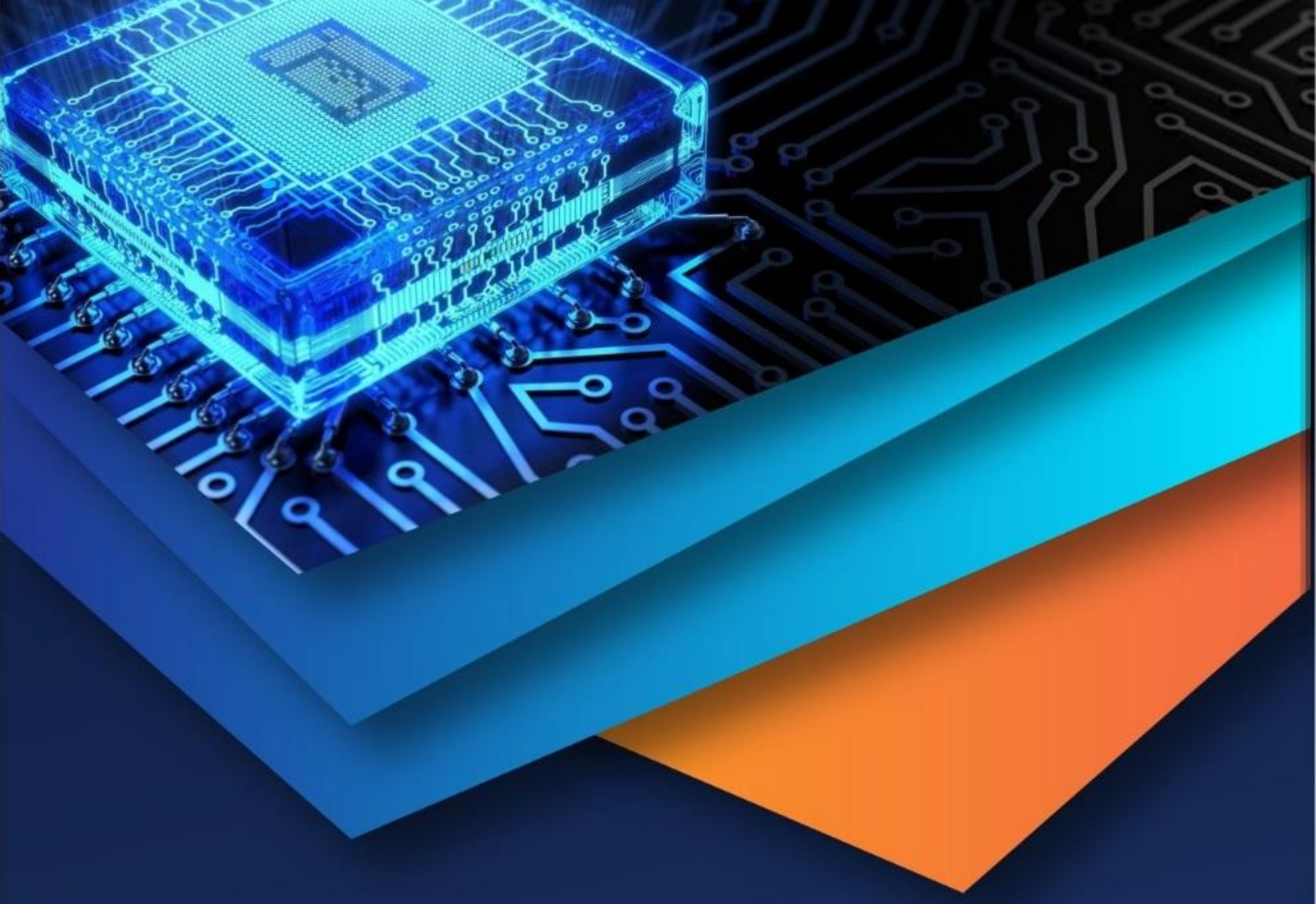

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