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Increasing Bending Strength of Aluminium Silicon Carbide Metal Matrix Composite Spur Gear by Increasing Fillet Radius

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Abstract: In this paper bending strength of spur gear teeth improved by increasing the fillet radius at root of the teeth. Spur gear geometry prepared using SolidWorks and imported in Ansys to analyse the stress and strain under specific loading condition. The fillet radius at root of teeth was increased from 0.15mm to 0.75mm with an increment of 0.15mm each time. With the increase in fillet radius of gear teeth, decrement of Von-mises stress, Von-mises strain and deformation of spur gear tooth is achieved indicating the improvement in bending strength of gear teeth. Metal matrix composite of Aluminium and Silicon Carbide is used as material for spur gear because of its good strength to weight ratio, low density, excellent castability and corrosion resistance. To verify the effect of fillet radius on strength of spur gear; stress, strain and deformation was found by increasing the load up to yielding limit of the material. The optimum value for the fillet radius at high loading condition achieved by graphical comparison.
Keywords: Spur gear, fillet radius, Al-SiC metal matrix composite, Von-mises stress and strain.

I. INTRODUCTON

Machines only work by transmitting the power from one component to another. To transmit power most efficiently the gear drives are applied. There are different types of gears on the basis of type of load and direction of transmitting torque. The most basic type of gear is spur gear. Due to the simplicity in manufacturing they are widely used in mostly every application. Spur gear has high load bearing capacity so they also used in heavy duty loadings.

Manufacturers around the globe has faced the problem of sudden machine breakdown. This would be very crucial happens due to the gear break down. Working continuously under load weakens the root of gear tooth. Tooth of the driven gear is weakest at the base just like the fixed end of cantilever. The torque which need to be transmitted, applied as tangential load on the top edge of the driven tooth (DIN 3990). This force resolved in two components, compressive or radial and tangential or horizontal components. The vertical or compressive component will give a negligible effect, so would not consider. The overall effect of the horizontal or tangential load observed. Hence it supposed to form a cantilever and leads to generate the bending stress at root fillet. Repeated working initiate the crack at the root and finally fails the material. To reduce the stress concentration, the sharp edges and corners must be removed. In spur gears the intersection of the profile curve of the tooth and root circle of gear form a sharp corner at the base of gear tooth. This cornered portion known as fillet at root of gear. But there are very few gear manufacturers who are given with the drawings mentioning this fillet's radius in it.

Fig.1 Circular fillet over Trochoidal fillet [11]

The formation of the gear by cutting motion of cutter the fillet will generated automatically, known as trocoidal fillet. During the running of the gear drive the stress concentrate on this edge. To reduce the value of stress at that part gears are provided with some circular fillet radius to smoothen the edge. With the help of this the stress will distributed throughout the tooth base instead of concentrated on edge only. This will increase the life of the spur gear in the drive.

Composites as material are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties that remain separate and distinct within the finished structure. The bulk material forms the continuous phase that is the matrix and the other acts as the discontinuous phase that is the reinforcements. While the reinforcing material usually carries the major amount of load, the matrix enables the load transfer by holding them together [8]. In this paper, the reinforced material is silicon carbide and the matrix material is aluminium. The composite material particles maintain their identities even after a composite material is fully formed.

The usage of Al-SiC Metal Matrix Composites has constantly increasing in the last few years due to their unique properties such as light weight, high strength, high specific modulus, high fatigue strength, high hardness and low density. Al-SiC composites of various silicon carbide compositions were produced using a centrifugal casting machine. The mechanical properties, tensile and compression strength, hardness and drop-weight impact strength were studied in order to determine the optimum silicon carbide percentage in the metal matrix composites. It was observed that the tensile and the compressive strength of the composites increased as the proportion of silicon carbide became higher in the composites. Also with increasing proportion of silicon carbide in the composite, the material became harder and appeared to have smaller values for total displacement and total energy during impact testing.

In this paper Al-SiC metal matrix composite (10% SiC particles) assigned as the material for spur gear. Than the gear is designed taking optimum design parameters, modelled in the design software (Solid works) followed by the investigation of von-mises stress, strain and deflection with the varying fillet radius. To examine the model for the effect of varying fillet radius we import the model in the Ansys software and apply Finite Element Analysis on it.

II. LITERATURE SURVEY

Good efficiency of the gear drive makes it more useful in many machines. Having so much demand and competition in manufacturing space forced the researchers to work on increasing the strength of gears. Many researchers throughout the globe gave ways in which they enhance the life of gear. They provide us with some literature through which we can study their work.

J.L Wood's et.al., [20] work incorporated the fillet radius with pre-setting of teeth. He proved analytically and experimentally the increment of bending strength and load carrying capacity by 43%. In his studies fillet radius effects on cutting tools, asymmetric tooth profiles, number of teeth are focused and with this he concluded stress reduction. After this the study on the trochoidal fillet and the work on advantages of circular fillet over trochoidal fillet comes into existence. Christos A. Spitas et.al., [18] replaced standard trochoidal fillet teeth with circular fillet teeth for stress analysis of teeth numbers varying from 9 to 40. During the same period Tengjiao Lin et.al., [15] worked on mesh generation of tooth root fillet, and prepare model for calculating the static and dynamic loading. S. Senthilvelon et.al., [19] during same year drag the attention towards the life of the gear. He found out that gear tooth fillet radius affects the polymer gear performance in terms of life, crack formation, deflection from mean position and heat generation during work. In this study it was found that fatigue life of 0.75 mm fillet gear is more than 0.25mm fillet. V. Senthil kumar et.al., [17] developed non-standard rack cutter of different fillet radius and found out that stress values reduced from 30.18 to 29.98 MPa. In these study small size gear, plastic material, steel and non-standard design incorporated with fillet variations and increment in strength is notice.

The study is not only limited to changing fillet radius, the effects are also being examined for different material, to get generalised solution. Instead of steel, plastic gears were examined for their load carrying capacity with changing root fillets radius. Harold van malick et.al., [16] has compared steel and plastic gear for changing root fillets and found that the root fillet of 0.3mm instead of 0.1mm reduces the stress value by 30%. The fine pitch gears for calculating the stresses at different tooth fillet radius were examined by A. Kapelevich et.al., [13] by fixing the number of teeth to 24 and diametral pitch equal to 12 and found the enhancement of bending strength. The strength of the gears could also be enhanced by changing the profile radius of alternate sides of same tooth. The asymmetric tooth profiles of the gear tooth a design modification to reduce the stress at the critical region. Th. Costopoulos et.al., [14] has studied the effect of fillet radius on stress of one sided involute asymmetric teeth for special cases. But in day to day working, the rotation in both the direction is required. So by modifying the design (changing profile for same tooth on alternate sides) model can be observed the reduction in stress by 28%. The change in the fillet radius will mostly show results on the smaller gears (gears with number of teeth 17 or less). Shanmugasundaram Sankar et.al., [12] work concentrated on the gear with number of teeth less than 17

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and the effect of fillet radius on it. According to Shanmugasundaram, this method does not show its benefits on big gears. But with further studies, change in fillet radius will stand its ground, that is, the reduction in stress value is not very large in bigger gear but its value is considerable. Ashwini Joshi et.al., [9] examined the reduction in stress and deflection value by changing fillet radius with number of teeth 14 to 30. N.L. Pedersen et.al., [4] studied the involute shape and then change the fillet radius, he observed the improvement in stress level by 3% to 8%.

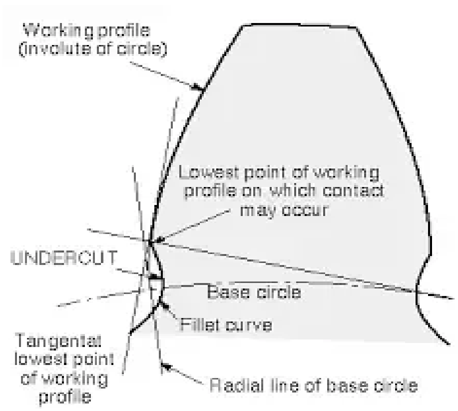

Fig.2 Undercutting in the spur gear [21]

The profile of tooth inside the base circle is radial. If the addendum of mating gear is more than the limiting value, it interferes with the dedendum of pinion and therefore two gears get locked. However, if a cutting rack having similar teeth is used to cut the teeth in the pinion, it will remove that portion of the pinion tooth which would have interfered with gear. A gear having its material removed in this manner is said to undercut and the process, undercutting. The fillet radius of rack cutter and non-traditional undercutting was studied by Ognyan Alipiev et.al., [6] and found the maximum value of the fillet radius for which there is no undercutting occur.

When the load is applied on the tooth during the meshing of gears, the tooth will start bending. This is not an immediate process, it's a gradual process. After long running of the gear drive, the cracks will initiate at the critical region. This critical region is the root fillet of the teeth, here the crack will initiate the propagation weakens the gear teeth and after some time fracture occur at the tooth base. This study is explained by Yogesh Pandya and Nizar Ahamed. Yogesh Pandya et.al., [7] worked on the crack path for different fillet radius and used a straight crack propagation for the higher values. He did all his study by incorporating patches, fine mesh generation, materials information and properties, radius values, crack path and finally find out their effects. Nizar Ahmed et.al., [5] study the propagation of crack in the tooth fillet for different values. The observations were taken for values ranging from 10% to 50% fillet crack.

After all these years of study in the spur gear every one studied every aspect of spur gear and the effect of the fillet radius on the stress. Atul Sharma, M.L. Aggarwal and Lakhwinder Singh [1] change the value of the fillet radius from 0.1mm to 0.5mm, and then record the readings of stress, strain and deformations, and ultimately gave an optimized design parameter. For this study they use a special material (aluminium silicon carbide metal matrix composite). In the present study the same material (aluminium silicon carbide metal matrix) used but the fillet radius varied from 0.15mm to 0.75mm just to give a more precise and optimized design to the spur gear. The analysis at different load also done to verify the effect on the material of spur gear.

III. METHODOLOGY

Methodology consists of the following steps:-

A. Design the Spur gear

The model of the spur gear was designed by taking the optimum parameters of the gear, like module number, number of teeth and pressure angle. With these parameters all other necessary parts such as pitch and pitch circle diameter, base circle diameter, addendum and dedendum factor, addendum and dedendum circle diameter, face width and circular pitch calculated using suitable relations.

S.No	Design parameter	Symbol	Description of calculative equation	Value
1.	Number of teeth	Z	Chosen value	16
2.	Module	m	Chosen value	2
3.	Pressure angle	Φ	Required value	20^o
4.	Pitch circle diameter	d	m × Z	32 mm
5.	Circular pitch	C.P	Π × m	6.28 mm
6.	Addendum factor	h_a	1 × m	2 mm
7.	Addendum circle diameter	d_a	$d + (2 \times h_a)$	36 mm
8.	Dedendum factor	h_f	1.25 × m	2.5 mm
9.	Dedendum circle diameter	d_f	$d – (2 \times h_f)$	27 mm
10.	Base circle diameter	d_b	d × CosΦ	30.07 mm
11.	Tooth thickness	t	1.6 × m	3.2 mm
12.	Face width	w	Chosen value	10 mm

Table-1. Design parameter and the calculation

Using the parameters give in the table-1, a model is prepared in the design software "Solid Works-2013". A 2D sketch is prepared with fillet radius 0.15 mm. The 2D sketch then convert to 3D model taking extrude length equal to the face width of gear.

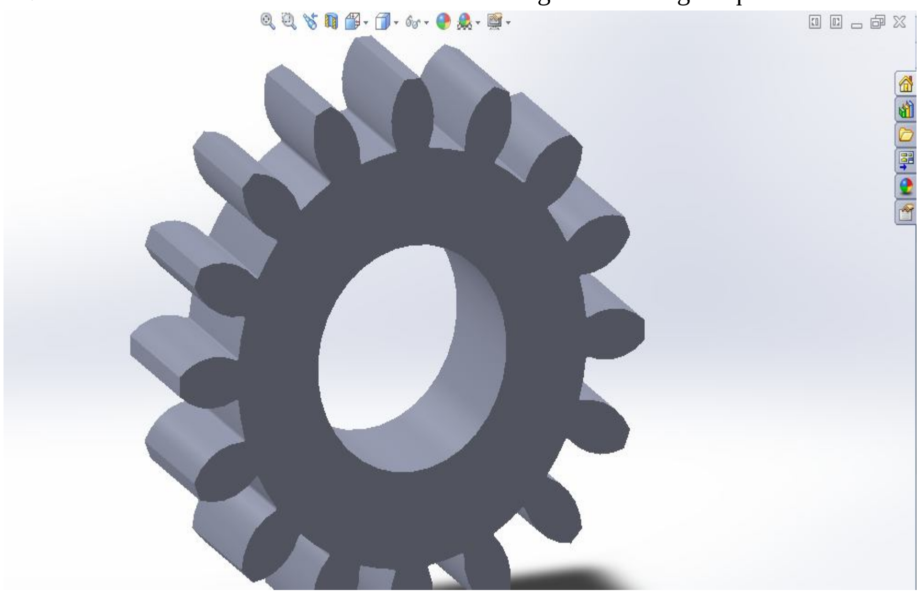

Fig.3 3D model prepared in the Solid Works-2013

B. Applying FEM on the model

The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical physics. It is also referred to as finite element analysis (FEA).The finite element method formulation of the problem results in a system of algebraic equations. The method yields approximate values of the unknowns at discrete number of points over the domain. To solve the problem, it subdivides a large problem into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. To apply FEM on the gear model it need to import spur gear model in analysis software (Ansys). This model saved in IGES format and that prepared 3d model's IGES file imported to Ansys-14.5 under the Static structure domain. All the loading and boundary condition applied here on the model for further solution.

IV. MATERIAL PROPERTY

After imported the spur gear model to Ansys, the properties of material to be used was assigned. Aluminium silicon carbide metal matrix composite chosen as the material for spur gear. Fill the properties of Al-SiC material such as young's modulus, yield strength, ultimate strength etc., as given in the table-2.

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PROPERTY DESCRIPTION	VALUES
Density	2.88 gm/cc
Young's modulus	1.15E+05 Mpa
Poisson's ratio	0.3
Yield tensile strength	487 Mpa
Ultimate tensile strength	690 Mpa

Table-2. Properties of Al-SiC(10%SiC) metal matrix composite

V. MESHING

Under the finite element analysis, we need to divide the model into many small elements. This process is known as the meshing. In this study Hex-Dominant method is used for meshing. Geometric shape of the elements is quadrilateral / triangular. After choosing this method fine element size were needed, for that we change the mesh centre quality as fine. The relevance will set to 50 to get a finely meshed model. This will give us more precise values of stresses. The number of node in the meshed model are 137339 while the elements numbers are 39947. It is better to have more numbers of the element until the effect of changing elements number will show no significant increase in the stress value.

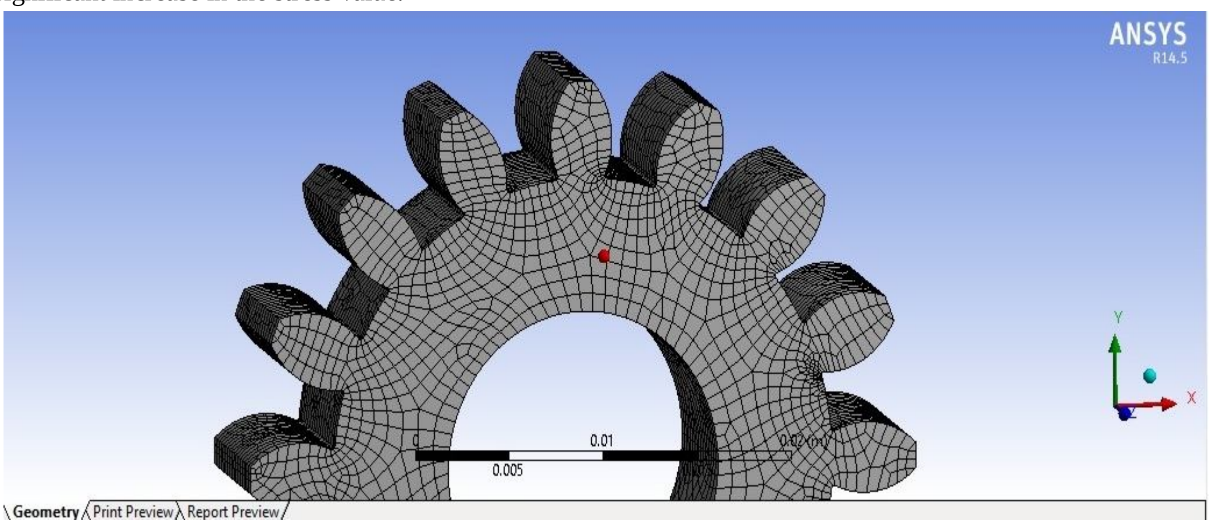


Fig.4 Meshed model of the spur gear with fillet radius 0.15mm (Hex-dominant)

VI. LOADING AND BOUNDARY CONDITIONS

Before applying the load supports are set to specify the constraints. The centre portion of spur gear where the shaft attached; set as fixed. Than 150N load is applied along the horizontal direction on the driving face of the tooth. In this way loaded tooth will act as the cantilever and show bending along the root of the tooth or at fillet. We can see the loading and boundary (support) condition in figure 5.

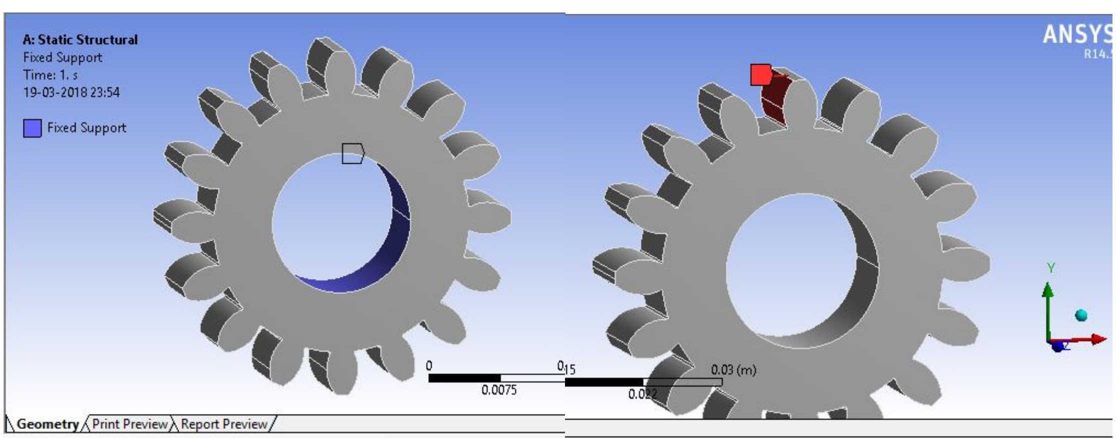


Fig.5 (a) fixed support from the centre portion.   Fig.5 (b) Force of 150N acting tangentially on the tooth

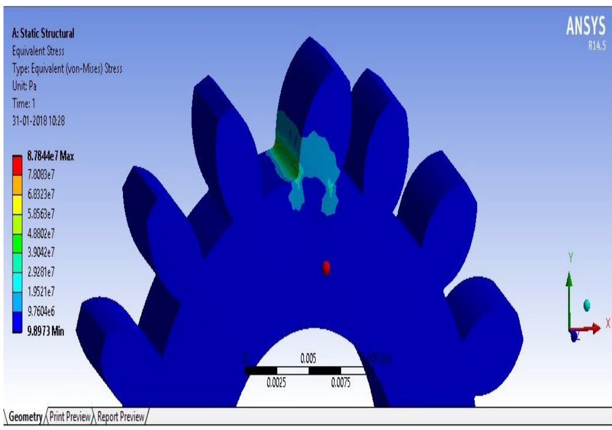
Blue colour in the figure 5(a) shows area held fixed whereas the portion appearing red in figure 5(b) indicates the face on which the force supposed to be acted tangentially, the arrow indicating the direction.

After applying the boundary and loading conditions examine the model for specific desirable solution. Here the Von-mises stress, Von-mises strain and total deformation was calculated. The results of the calculation done by the software is given in the result analysis.

VII. RESULT ANALYSIS

A. Effect Of Varying Fillet Radius (0.15mm To 0.75mm)

Spur gear models was prepared with fillet radius 0.25mm, 0.35mm, 0.45mm, 0.55mm, 0.65mm, and 0.75mm in the SolidWorks and imported to Ansys for further analysis. Al-SiC metal matrix composite was assign as material for all spur gears. Then pre-processing such as applying meshing, setting boundary condition, applying load done on gears with varying fillet radius and finally solve for results. Solution gave the value of Von-mises stress, strain and total deformation for all spur gear. The value of Von-mises stress at 150N load for fillet radius 0.15mm was 87.84 N/mm^2, and the same for the fillet radius 0.45mm decreased and reaches to 52.59 N/mm^2. Value of stress further decreased for fillet radius 0.75mm and noted 43.03 N/mm^2.



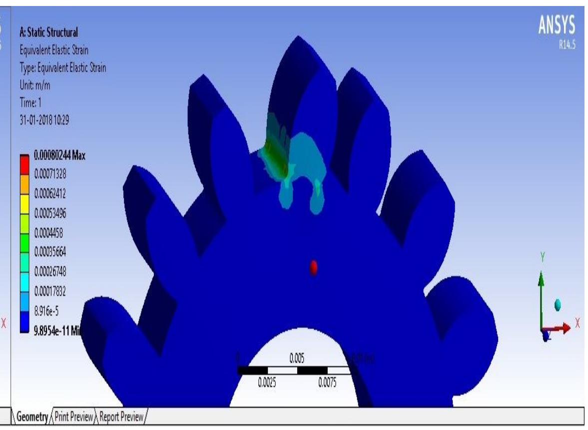


Fig.6 (a)Von-mises stress gear with fillet radius 0.15mm Fig.6 (b)Von-mises strain on gear with fillet radius 0.15mm

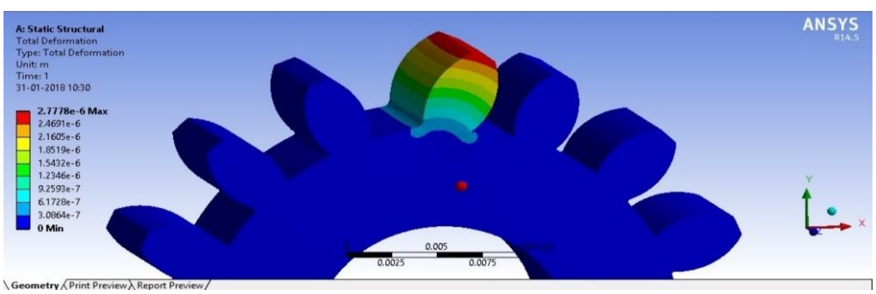
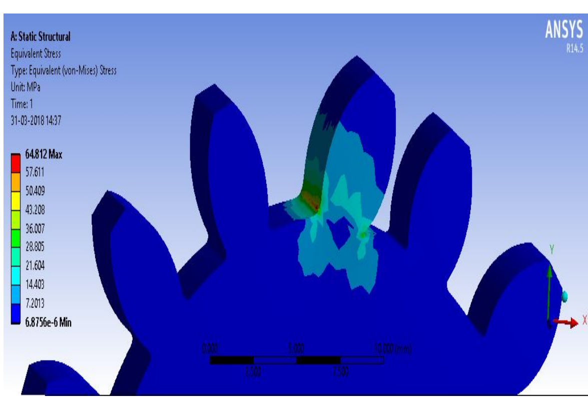


Fig.6 (c) Deformation of gear tooth with fillet radius 0.15mm



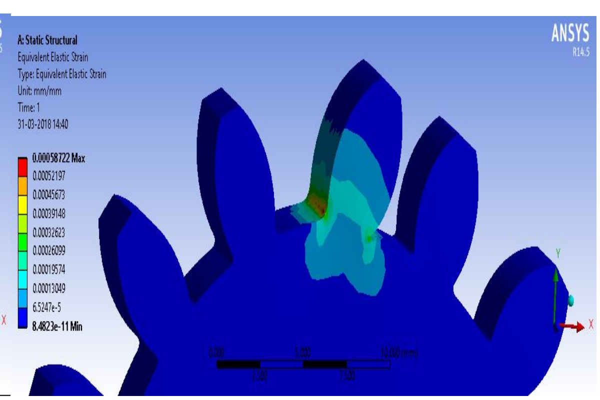


Fig.7 (a) Von-mises stress at fillet radius 0.25mm Fig.7 (b) Von-mises strain at fillet radius 0.25mm

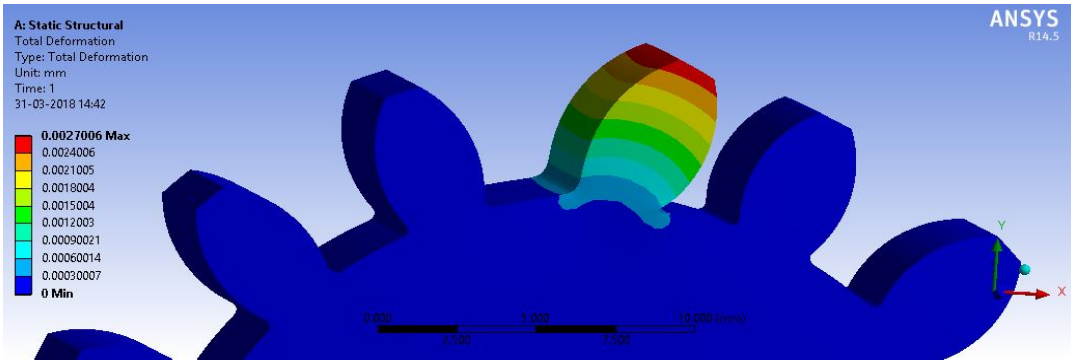


Fig.7 (c) total deformation at fillet radius 0.25mm

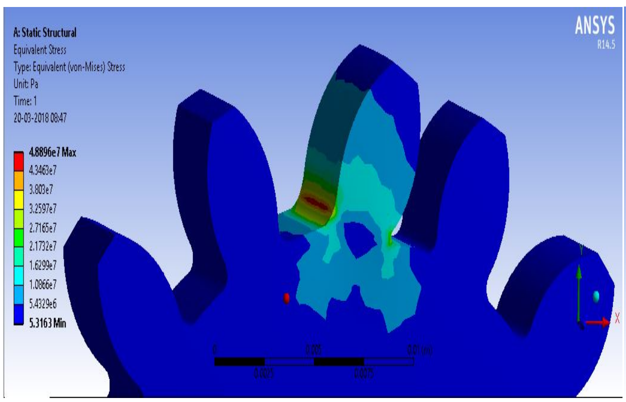


Fig.8 (a)Von-mises stress at fillet radius 0.55mm

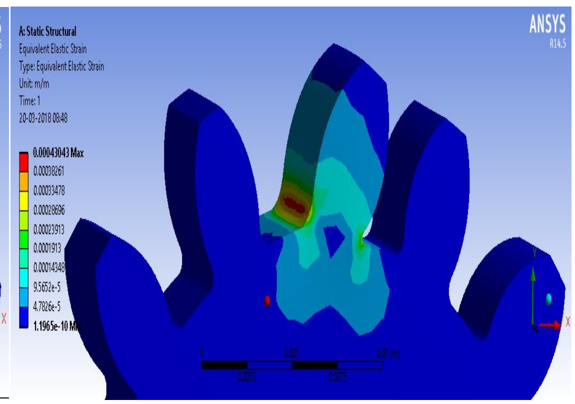


Fig.8 (b)Von-mises strain at fillet radius 0.55mm

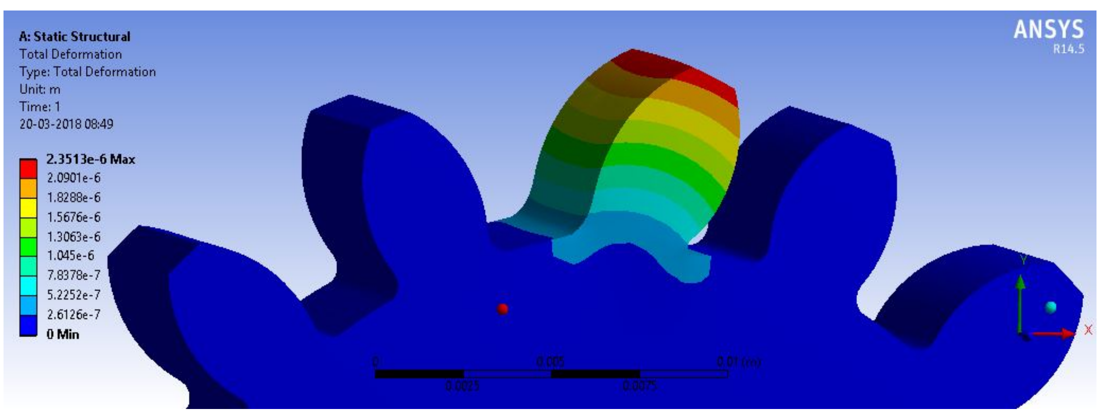


Fig.8 (c) Total deformation of tooth with fillet radius 0.55

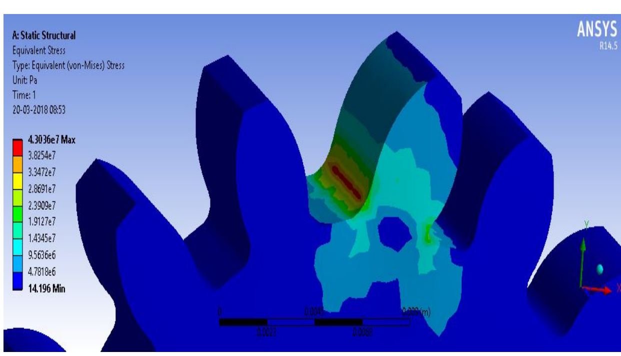


Fig.9 (a) Von-mises stress at fillet radius 0.75mm

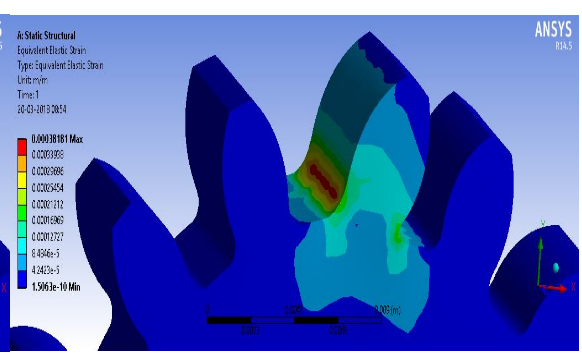


Fig.9 (b)Von-mises strain at fillet radius 0.75mm

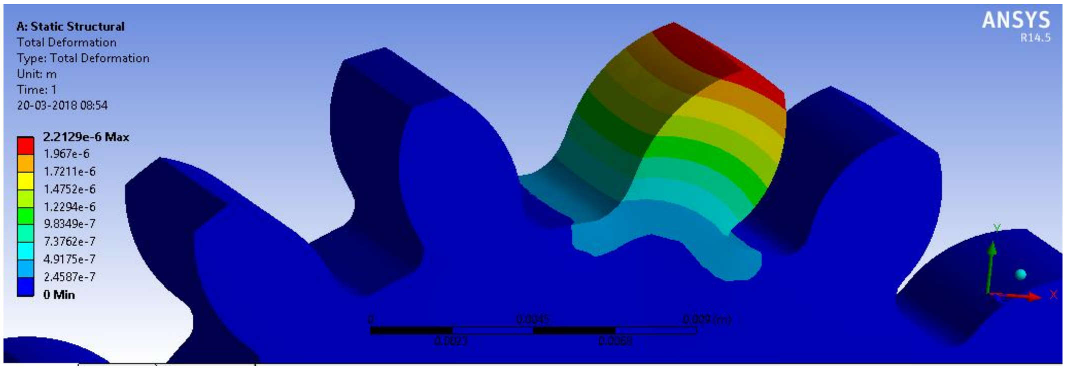


Fig.9 (c) Total deformation of tooth with fillet radius 0.75mm

Figure 6(a), 7(a), 8(a) and 9 (a) shows the model under load of 150N and presenting Von-mises stress. It can be seen that the red colour appeared on the fillet or the root of the tooth signifies the critical region during the loading of the gear. Red colour indicates the maximum stress in the region. Similarly figure 6(b), 7(b), 8(b) and 9(b) shows the strain at the root of the gear tooth, on the application of load of 150N. Von-mises stress, strain and total deformation also calculated for the higher value of applied force. Load of 500N, 750N and 1000N applied on the tooth face. Result for stress, strain and deformation were plotted in the graphs.

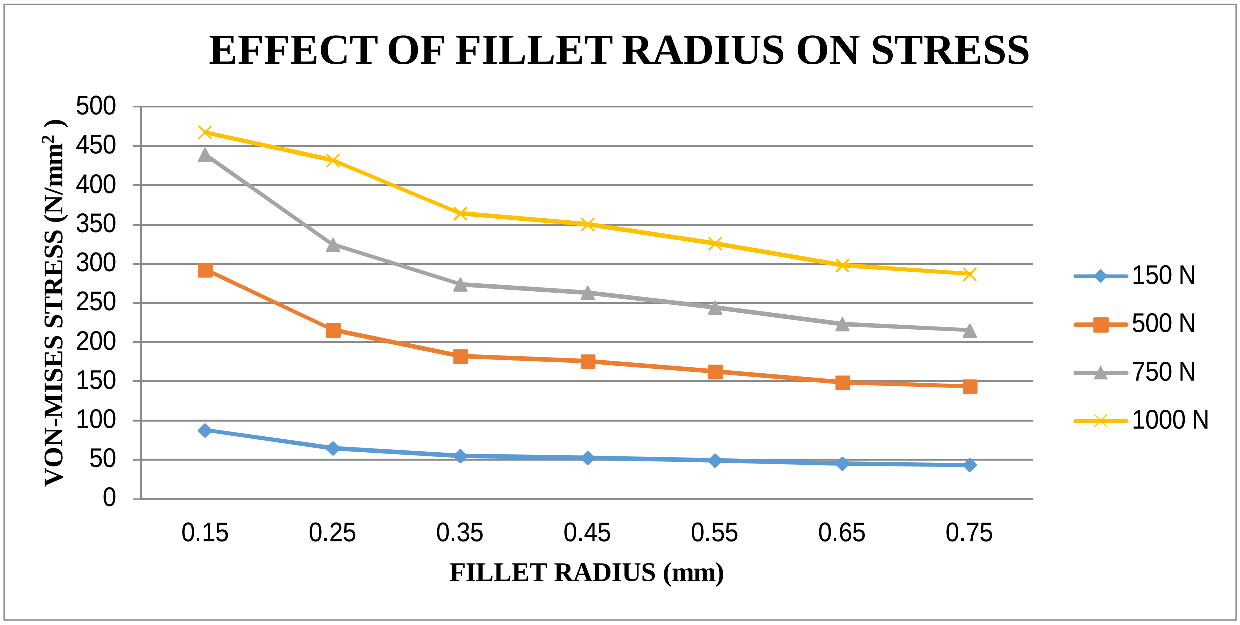
Figure 6(c), 7(c), 8(c) and 9(c) gives the total deformation of the tooth from its original mean position after applying 150N load. Here the top most part deform maximum as it is farthest from the root. The effect of fillet radius on the stress, strain and deformation at load of 150N has been tabulated in table 3.

Fillet radius (in mm)	Number of nodes in meshing	Number of elements in meshing	Equivalent Von-mises stress (N/mm^2)	Equivalent Von-mises strain (m/m)	Total Deformation (m)
0.15	137339	39947	87.84	8.02×10^{-4}	2.778e-6
0.25	88980	24146	64.81	5.87×10^{-4}	2.7006e-6
0.35	99993	27944	54.68	4.77×10^{-4}	2.539e-6
0.45	93198	25908	52.59	4.66×10^{-4}	2.454e-6
0.55	91888	25393	48.89	4.30×10^{-4}	2.351e-6
0.65	92848	25522	44.66	3.92×10^{-4}	2.301e-6
0.75	90678	25403	43.03	3.81×10^{-4}	2.212e-6

Table.3 Effect of varying fillet radius on the Von-mises stress, strain and total deformation at load of 150N

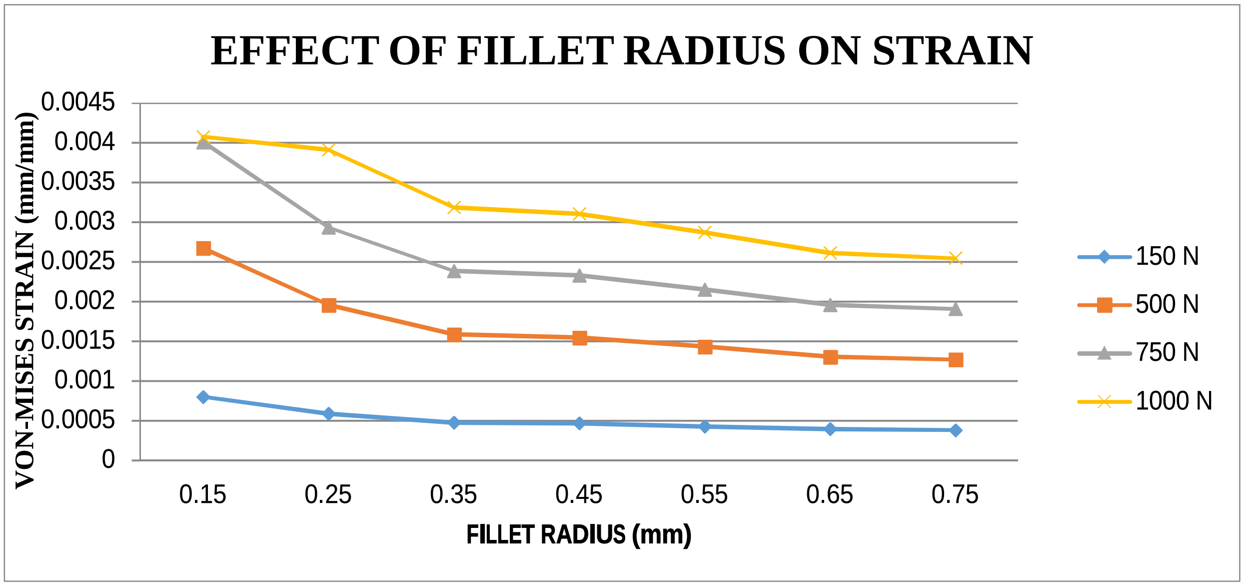
The increasing value of the fillet radius make sure that there should not be any interference between the meshing teeth of the gears. In the table-3 the considerable reduction in the Von-mises stress, Strain and deformation was observed. At 150N of load the fillet radius is increased from 0.15mm to 0.75mm results in the reduction of stress from 87.84 N/mm^2 to 43.03N/mm^2 which is 51% decrease in the stress. The equivalent strain has reduced from 0.000802 to 0.000381 which is about 52% and the total deformation has decrease from 2.77e-6 m to 2.21e-6m about 20%.

Variation of stress, strain and deformation with respect to change in fillet radius compared in graphs. Graphs show the reduction of stress, strain and deformation on increasing the fillet radius was similar even at the higher value of load such as 1000N.



Graph:-1 Variation of Von-Mises stress with respect to fillet radius under different loads

Graph-1 shows the decreasing slope of stress with increasing values of fillet radius. Value of Von-mises stress for different loads (150N, 500N, 750N and 1000N) shows approximately same decreasing curve. Slope of the stress line for gear having fillet radius 0.15mm to 0.25mm and 0.35mm is sharper if compared to gears with other fillet radius. The slope is little higher for the greater load values. Overall reduction in stress is same at all load (51%) except 1000N, at this the reduction is 38%. Further increase in load is not recommended as it will start yielding the material and the gear will fail. Graph shows that if load increased further from 1000N the gear material will fail only for the 0.15mm fillet radius, the gears having fillet radius 0.25mm and more are safe as it will not cross its yielding limit.



Graph-2:- Variation of Von- Mises strain with respect to fillet radius under different loads

Graph-2 shows the variation of the Von-mises strain with the increasing value of fillet radius at different loads. In graph, the strain for 0.15mm fillet radius spur gear at 1000N of load showing approximately same value as that for 750N load. The reduction slope for the strain line for 1000N load is less as compare to the slop of strain line of other lower load. But after 0.35mm fillet radius the reduction slope of strain is similar for all load lines.

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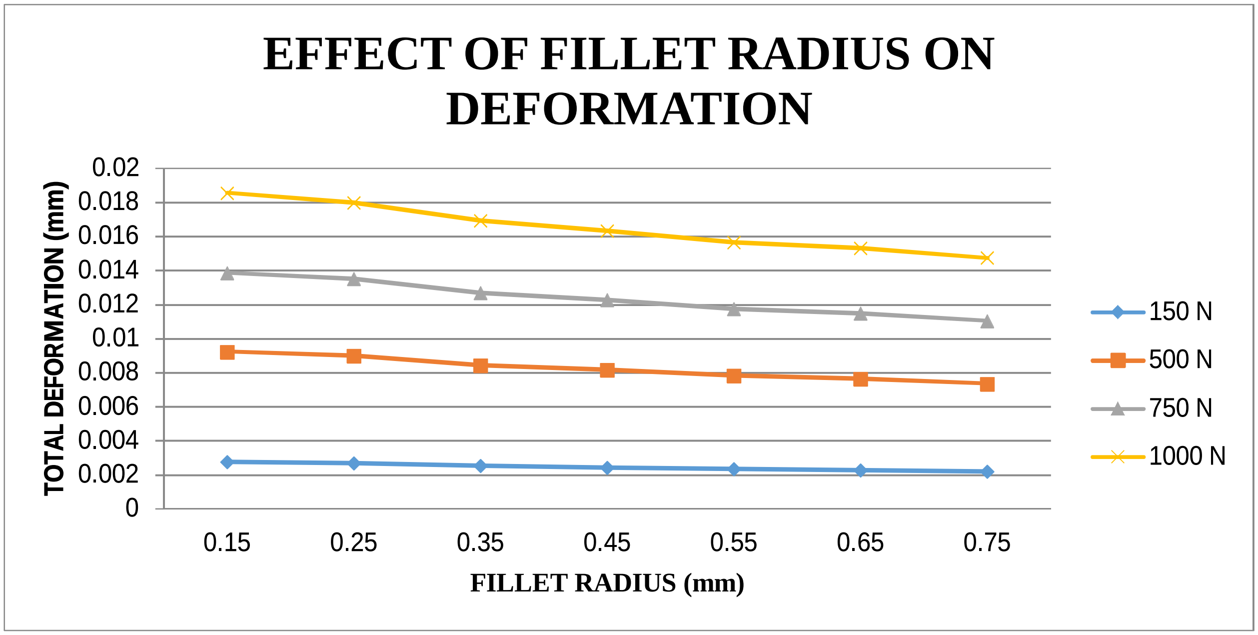

Graph-3:- Deformation of tooth with respect to fillet radius at 150N load under different loads

Graph-3 represent the total deformation of the gear tooth with increasing fillet radius deformation at different loads. Compared to stress and strain graphs, the deformation plot does not show the variation with the varying load condition. The slop of the dformation lines are similar at all values of load, which shows that the deformation of the tooth of spur gear will decrease with increase in the fillet radius but it does not affected by the loading condition very much.

VIII. CONCLUSION

The effect of increasing fillet radius of the teeth at the root, reduces stress concentration in critical area of spur gear made of metal matrix of aluminium silicon carbide. Due to which strain and deformation also decreases with increase in fillet radius. Plot shows the linear relation between fillet radius and Von-mises stress, strain, and deformation. The variation in the value of stress when fillet radius increase from 0.65mm to 0.75mm is less, which conclude that further increase in fillet radius does not reduce stress considerably. Hence 0.75mm is the optimum value of fillet radius for specific spur gear. The increasing load beyond 1000N will fail the material as it reaches its yielding limit, but this study conclude that the spur gear will not fail if the fillet radius is greater than 0.15mm. By increasing the fillet radius at the root of spur gear tooth the load carrying capacity of the gear increase. The increase in value of fillet radius is restrained by the fact that there should not be any interference.

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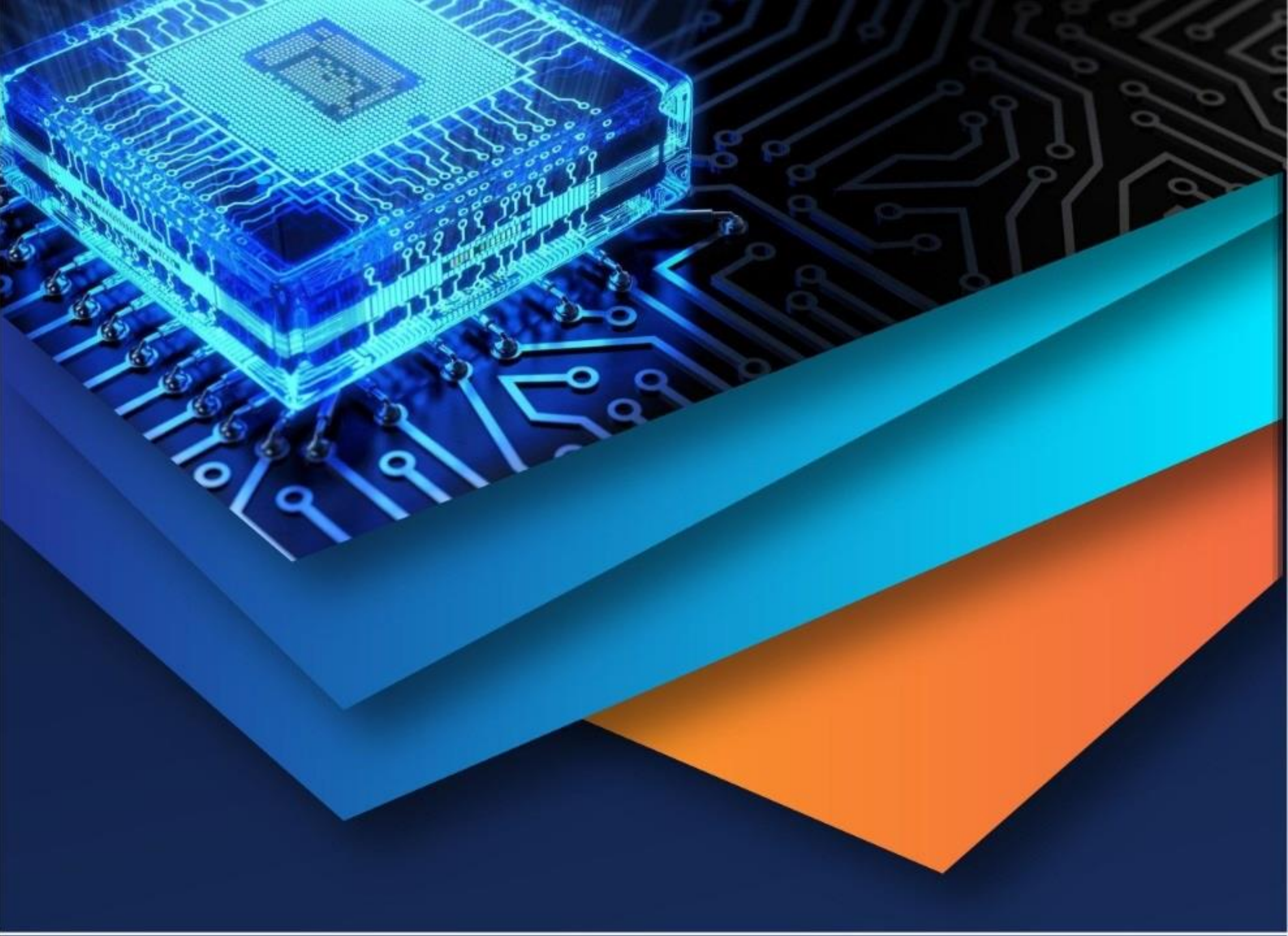

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