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Numerical and Theoretical Analysis of a Spur Gear Using Composite and Conventional Materials

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HIGHLIGHTS

- Different materials were investigated and compared for a spur gear using theoretical (Hertzian contact) and numerical analysis (ANSYS) to reduce the spur gear's weight while keeping their useful properties.
- A three-dimensional spur gear was designed, modeled, and simulated using ANSYS software.
- Five materials were used: two conventional materials (stainless steel and copper alloy) and three different composite materials, including 50% Carbon Epoxy Resin, 1.5% Filler containing Acetal, and glass-filled polyamide.
- Among the different presented materials, 50% carbon epoxy resin was the optimal material for spur gear fabrication due to its high strength and low density.

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ABSTRACT

A spur gear is one of the most common forms of precision cylindrical gear. In the industry, reducing the weight of gears while keeping their useful properties has become an even more pressing challenge. As a result, the investigators have made many attempts to reduce the weight of the gears. Despite these efforts, the problem still requires more research. This study presented a spur gear's modeling and finite element analysis using different materials. A three-dimensional spur gear was designed, modeled, and simulated using ANSYS software. Five different materials, including two conventional materials (stainless steel and copper alloy) and three different composite materials, including 50% carbon fibers reinforced in epoxy resin, 1.5% filler containing acetal, i.e., Graphene Reinforced Acetal, and glass-filled polyamide. Composites were fabricated by varying the graphene quantity in Acetal nanocomposites. The spur gear stress was calculated theoretically using the Hertzian equation, and FEM was analyzed using ANSYS 14.0 under limited loading conditions and rotational speed. Although the obtained results showed that both methods were comparable, there was a significant difference between the two methods when 50% carbon fibers reinforced in epoxy resin matrix were used, which is Hertzian analysis was 250.13 MPa. In contrast, this result was reduced up to 152.13 MPa in FEM. The study concluded that among the different presented materials, 50% carbon fibers reinforced in epoxy resin matrix were the optimal material for spur gear fabrication due to their high strength and low density. Hence, the spur gear material can be replaced by 50% carbon fibers reinforced in the epoxy resin matrix.

1. Introduction

Gear is a cylindrical wheel tooth cut meshed with another gear for transmitting power from one shaft to another during motion. Their practical application in modern engineering systems ranges from tiny wristwatches to huge machinery equipment such as rolling, automobile, aerospace industry, transmitting machinery, hoisting, and marine engines [1]. Among them, the spur gear is the simplest, most common, and cost-effective type used for transmitting power because of having straight teeth cut on the rim parallel to the axis of rotation. The spur gear is used in oscillating sprinklers, electric screwdrivers, windup alarm clocks, clothing dryers, and washing machines [2]. The contact between two teeth follows the line of action. When contact is placed between the root and the pitch circle of the driving wheel in the meshing first half, the friction force is moved towards the root

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of the driving tooth. As a result, the rotation will be counteracted. When the contacted teeth pass through the pitch circle, the friction force alters direction and acts to the rolling motion. Also, this direction is reversed to the following teeth. Thus, relative motion is fixed across the contact width but changes during the interaction [3]. The normal or resultant force acts along the pressure line at the pitch point, which solves both tangential and vertical components in a horizontal and vertical plane. The tangential force component calculates the torque and power of spur gears [4]. When the tangential load acts on the gear, several stresses are produced, but the most severe types of stress are contact stress and bending stress. If contact stress on the gear is higher than the wear strengths of the gear material, failure of the gear is taking place. This is called wear or pitting failure of the gear. Tensile stress is the primary cause of gear tooth failure. The key factor in the fatigue life of the spur gear is maximum principal stress [5]. Pitting is a surface fatigue failure caused by high contact stress repetitions [6].

Furthermore, the other problem of the gear system is noise and vibration, which are caused by transmission errors between mating gears. The error is defined as the difference between the theoretical and the actual position between gear and pinion [7]. In addition, due to increasing demands on gears in various applications in engineering technology and significant gear roles in transmitting power, the gears fail when the gear teeth operate at stress levels that exceed the stress. Therefore, gear material needs to be a general concern. The use of composite materials has increased in recent years due to their high specific stiffness and strength, weight reduction properties with enough strength, corrosion resistance, high impact energy absorption, and many more [8]. The researchers have attempted to investigate the induced stress in the two mating gears. Accordingly, Shanavas [9] examined the bending and contact stress of mating gears to investigate the static stress characteristics of an involute composite spur gear system compared with those of the involute cast iron spur gear system. The researcher aimed to replace the cast iron with a carbon fiber epoxy composite spur gear. The modeling was done by a CAD system (PRO/ENGINEER), and the FEM was done using ANSYS 13. The obtained results concluded that the cast iron spur gear can be replaced by a composite carbon fibre reinforced epoxy spur gear. This is because carbon fibre reinforced epoxy spur gear orientation of laminates was 90 degrees stronger than cast iron spur gear. The same attempt was made by Mahendran *et al.* [10] for the composite material (fiber composite) to design and analyze spur gear and compare it with metallic material cast steel. The obtained results showed that the deformation, induced stress, and weight of composite material are less than those for cast steel. Nath Anuj and A.R. Nayak [11] did the same research study as Mahendran *et al.* [10] did. Still, they changed the composite material, which was 50% carbon fibers reinforced in an epoxy resin matrix, and despite that, they changed the value of torque and speed at various ranges and got the same result. Further investigation of spur gear was done by Arunkuma *et al.* [12] using polyoxymethylene with cast iron in a sugarcane juice machine. The bending stress was calculated and the gear was analysed using the ANSYS Workbench. The obtained results, including von-Mises stress, strain and deflection showed that the polyoxymethylene was within the allowable limit and could be replaced with the cast iron.

Pawar and Output [13] examined the study to replace the composite material (Aluminum based SiC) matrix with metallic gear. The modeling and finite element analysis of gears were done by ANSYS 14.0. They concluded that the composite gear provided almost 60% less weight than steel gear with the same power rating. In addition, Dhomse and Agrawal [14] utilized the polymer PEK material in designing and analyzing the spur gear. They compared PEK gear results with metallic cast iron under limited loading conditions and realized that using plastic gear reduces vibration, noise, and weight. The investigated results showed that PEK spur gear had more strength than cast iron spur gear with lower density. They concluded that high strength, the noise-free motion of gears, and low weight were achieved when replacing cast iron with PEK gears.

Rahat. and Marine [15] stated that composites are stronger in weight ratio, hardness, and fewer chances of failure; thus, improved mechanical properties can be obtained. The research concerned the investigation of replacing metallic material with composite material, which was aluminum silicon carbide. The study revealed that using composite material reduced stress by nearly 25%. Another attempt was made by Singh Mohit *et al.* [16] for metallic gear of steel alloy and composite gear of aluminum-silicon, carbon fiber epoxy carbon, and carbon fiber silicon carbide ceramic. Rajeshkumar and Manoharan [17] investigated the parametric design of the composite gear, Peek material, and steel and examined the contact stress using ANSYS software. They concluded that steel and plastic materials deformation was higher than composite materials. Ramanjaneyulu *et al.* [18] used 1.5% composite material as graphene-filled acetal copolymer composites, polycarbonate, and metallic material cast iron for design spur gear. The Finite Element Method carried out the design and analysis of composite spur gear. The obtained results showed that 1.5% graphene reinforced acetal copolymer gears were much better in cost, weight, and performance compared to metallic and polymer gears. Moreover, Devi [19] used composite material short carbon reinforced (SCF) nylon and conventional material cast iron or mild steel for the design, model, and FE analysis of spur gear. According to the results, cast iron or mild steel can be replaced with short carbon reinforced (SCF) nylon for limited load applications under the power of 1500 watts.

However, so many previous researchers studied the contact stress of composite material of spur gear using the finite element method, ANSYS, and theoretical Hertzian equations. Each of them presented one or two composite materials and conventional materials. Despite that, they compared the composite material with conventional materials using the effect of parameters like design spur gear and bending stress using Lewis's equation. Unfortunately, research on composite spur gear materials is still limited to contact stress analysis of composite materials, even though materials play an important role in gear manufacturing by reducing failure, noise, and vibration. Therefore, this work aimed to use the Finite Element Method (ANSYS) to compare the conventional with composite materials for a spur gear to select an optimal material for spur gear. Thus, this research presented several materials, including conventional and composite materials, and a comparison between the finite element numerical solutions and the theoretical Hertzian method was conducted. The next section explains the theoretical background and mathematical equations of the Hertzian method. Then the results and discussion are shown, while the conclusion of this research is presented in the last section.

2. Gear Modelling and Analysis

2.1 Material Selection

This study used five different materials: stainless steel, copper alloy, 50% carbon fibres reinforced in epoxy resin, 1.5% filler containing acetal, and glass-filled polyamide. The first two materials are conventional, whereas the other three materials are composite materials to deal with the contact stress, which is their mechanical properties are illustrated in Table 1.

Table 1: Mechanical property of gear materials [11, 18, 20, 21]

Materials	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio	Tensile strength (MPa)
Stainless steel	7750	1.95e5	0.31	583
Copper alloy	8300	1.1e5	0.34	430
50% Carbon fibers reinforced in epoxy resin	1800	4.5e5	0.3	52
1.5% Filler contained acetal	1410	3092.12	0.36	70
Glass filled polyamide	840	5910	0.314	38.1

2.2 Gear Specifications

The spur gears have a power consumption of 10 kW, a rotating speed of 1500 RPM, and a face width of 25.4 mm. As a result of these parameters, the dimensions of the spur gear are calculated as indicated in Table 2.

Table 2: Spur gear specifications

Part dimension	Symbol	value
No.of teeth	Z	20
Pressure angle	$\emptyset$	20
Module	M	6.35
Pitch circle diameter	d_p	127
Face width	L	25.4
Dedendum circle diameter	da	139.7
Addendum circle diameter	dd	111.76

All dimensions are in mm

2.3 Theoretical Analysis (Hertzian Contact)

Pitting is one of the main factors for tooth failure in the two mating gears. This failure is known as a surface fatigue failure which occurs because of the repetition of contacting the teeth of two gears. Thus, high contact stress is produced between the gear teeth during the transmitting power. The contact stress of gears is computed by Hertzian theory. The Hertzian theory can be derived from contact between two cylinders, as shown in Figure 1.

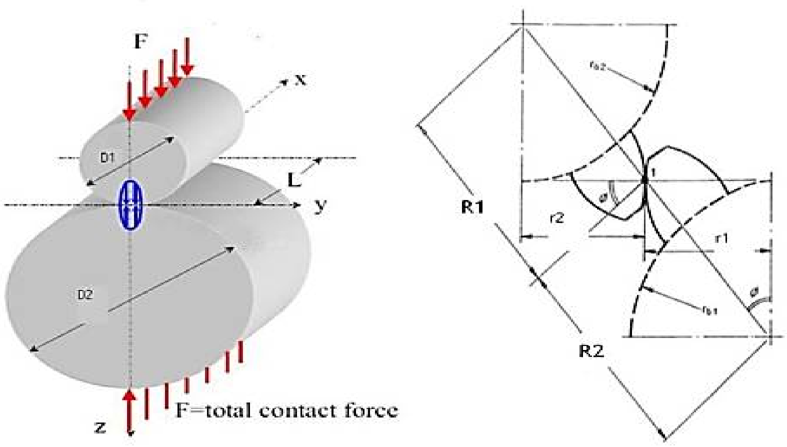

Figure 1: Cylinders in contact [7]

Based on the Hertzian theory, the mathematical equations of maximum contact stress, hertz stress, compressive stress, or contact pressure are:

$$P_{\max} = \sigma_H = \frac{2F}{\pi b L} \tag{1}$$

$b = \sqrt{\frac{2F}{\pi L}\frac{\frac{(1-v_1^2)}{E_1}+\frac{(1-v_2^2)}{E_2}}{\frac{1}{d_1}+\frac{1}{d_2}}}$ Then the maximum value of contact stress in gear teeth according to the Hertzian equation can be estimated by:

$$\sigma_c = \sqrt{\frac{F}{\pi L}\frac{\left[\frac{1}{r_1+\frac{1}{r_2}}\right]}{\left[\frac{(1-v_1^2)}{E_1+\frac{(1-v_2^2)}{E_2}}\right]}} \tag{2}$$

To use the contact stress equation for a pair of teeth contacting in contact point, the r_1, r_2 should be replaced by the radius of curvature at the pitch point [20] Therefore

$r_1 = \frac{d_{pp}\sin\phi}{2}$ and $r_2 = \frac{d_{pg}\sin\phi}{2}$

A pair of gears have the same geometry, so:

$d_{pp} = d_{pg} = d_p$

so, $r_1 = r_2 = r = \frac{d_p \sin\phi}{2} = r_p \sin\phi$

hence, $\sigma_c^2 = \frac{FE}{\pi L r_p (1-v^2)\sin\phi}$ $F = \frac{F_t}{\cos\phi}$

$$\sigma_c^2 = \frac{E}{\pi(1-v^2)}\left[\frac{F_t}{L r_p \sin\phi\cos\phi}\right] \tag{3}$$

$$\text{Where } F_t = \frac{2T}{d_p} \tag{4}$$

$$P = \frac{2\pi n_p T}{60\times10^6} \text{ then } T = \frac{60\times10^6\times P}{2\pi n_p} \tag{5}$$

$$\sigma_{ca} = \frac{\sigma_c}{SF} \tag{6}$$

3. Numerical Analysis

3.1 Modeling

ANSYS workbench 14.0 was used for modeling a 3D spur gear based on the specifications presented in Table 2. The gear was modeled and sketched by giving the coordinates of the involute curve from the involute equation and producing the profile of an involute spur gear, as shown in Figure 2 When the geometry of spur gear was created, the static structure was chosen in ANSYS, as shown in Figure 3. Then the material properties of spur gear were added according to the presented material properties in Table 1.

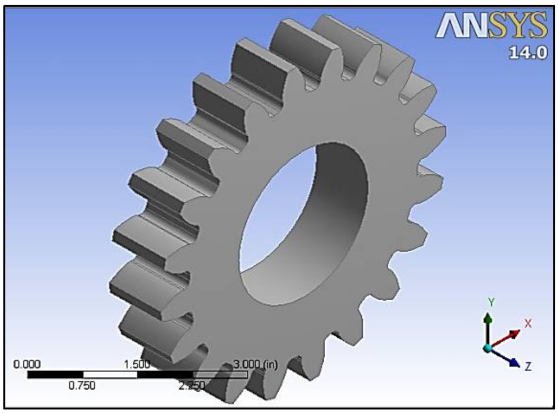

Figure 2: 3D model of the spur gear

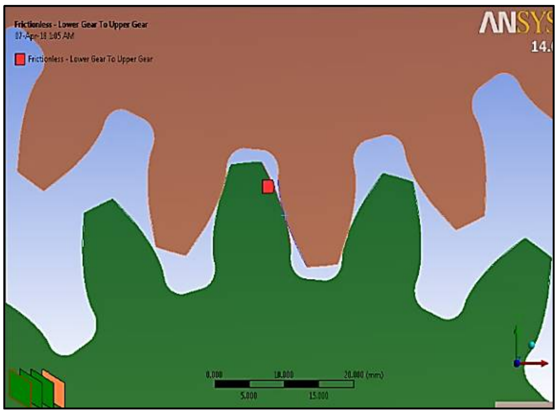

Figure 3: Contact area of two mating gears

3.2 Automatic Mesh Generation

One of the most important parts of engineering simulation is mesh creation. ANSYS meshing technology makes it feasible to balance these demands and obtain the best mesh for each simulation in the most automated manner possible. The 3D gears are meshed, containing 8151 nodes and 2369 elements, as shown in Figure 4.

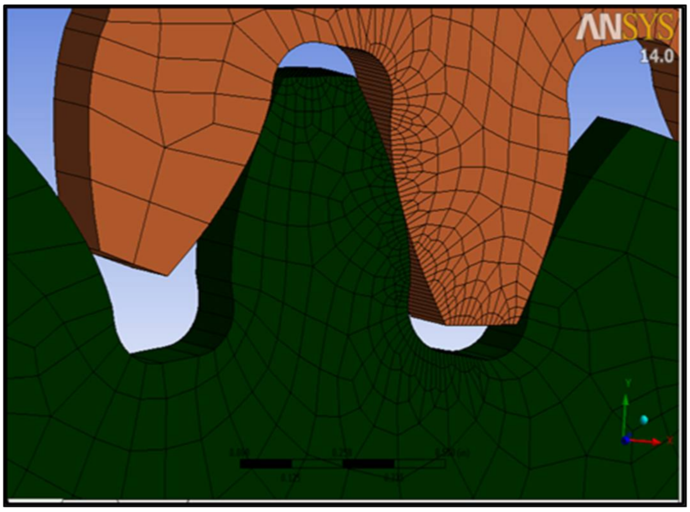

Figure 4: Spur gear meshing

After meshing the 3D geometry of the two gears, the boundary conditions are applied to the two gears: for the lower gear, fixed support is applied, and for the upper gear, frictionless support. Then the moment is applied on the inner rim of the upper gear in a clockwise direction as a driving torque, and rotational velocity is applied on the Z-axis to the fixed center of the rotation, respectively, in various ranges in a counterclockwise direction, as shown in Figure 5. After setting all the conditions, the software is run, and the minimum and maximum equivalent contact stress between the two gears is analyzed over the contact area. The finite element solution with ANSYS software can predict local stress at each point.

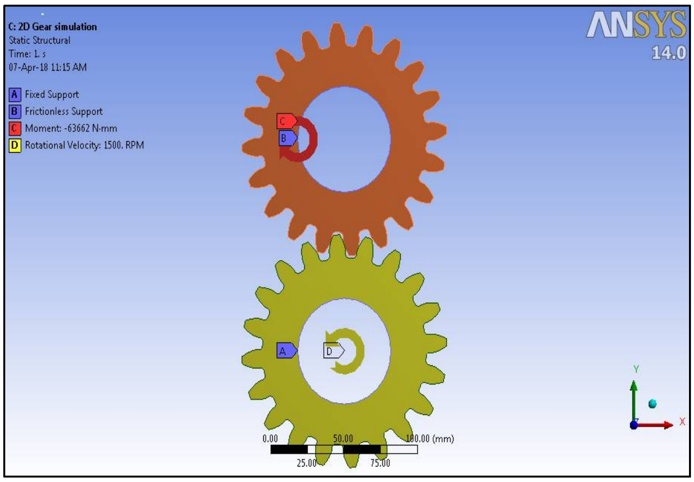

Figure 5: Spur gear boundary condition

4. Results and Discussion

In this study, the contact stresses of a spur gear made from different materials were compared using theoretical (Hertzian contact) and numerical (ANSYS) analysis to pick the best material for the spur gear.

To compare the difference between the two analyses, the transmitted torque for two gears was calculated using Equation (5), which is 63662 *N-mm* for 10 *kW* of transmitted power and 1500 *RPM* rotational speed. Then Equation 3 is used to calculate the contact stress between the two gears, and finally, Equation (6) is used to calculate the maximum allowable contact stress by considering the 2.5 safety factor.

For different materials of the spur gear, the von Mises stress analysis was performed numerically. After that, the computed values were compared to those determined theoretically utilizing the Hertzian equation. To clarify the distribution of von Mises stress and strain in a spur gear, we suffice with the two figures below (Figure 6 and 7). As for the rest of the materials used in this research, we only mention the maximum and minimum values. Figure 6 A and B compares the stress distribution and maximum von-Mises stress for the stainless steel and 50% carbon fibers reinforced in epoxy resin, respectively. While for the other materials, such as copper alloy, 1.5% filler contained acetal and glass-filled polyamide. Only the maximum and minimum values were mentioned in this paper (see Table 3). The result shows that the maximum stress of steel is approximately 128 MPa, while the maximum stress of 50% carbon fibers reinforced in epoxy resin is approximately 152 MPa. The maximum stress in the other materials is as follows: for the copper alloy is 117 MPa, while for 1.5% filler contained acetal is 33 MPa and for glass filled polyamide is 45 MPa.

The employment of various materials in gear production results in various contact stresses. This spectrum of contact stresses and deformation is important in material selection for many purposes. The results derived using the Hertzian equation and ANSYS are consistent. Furthermore, it demonstrates that the ANSYS simulation is compatible with and can handle the Hertzian equation for various materials employed in the study.

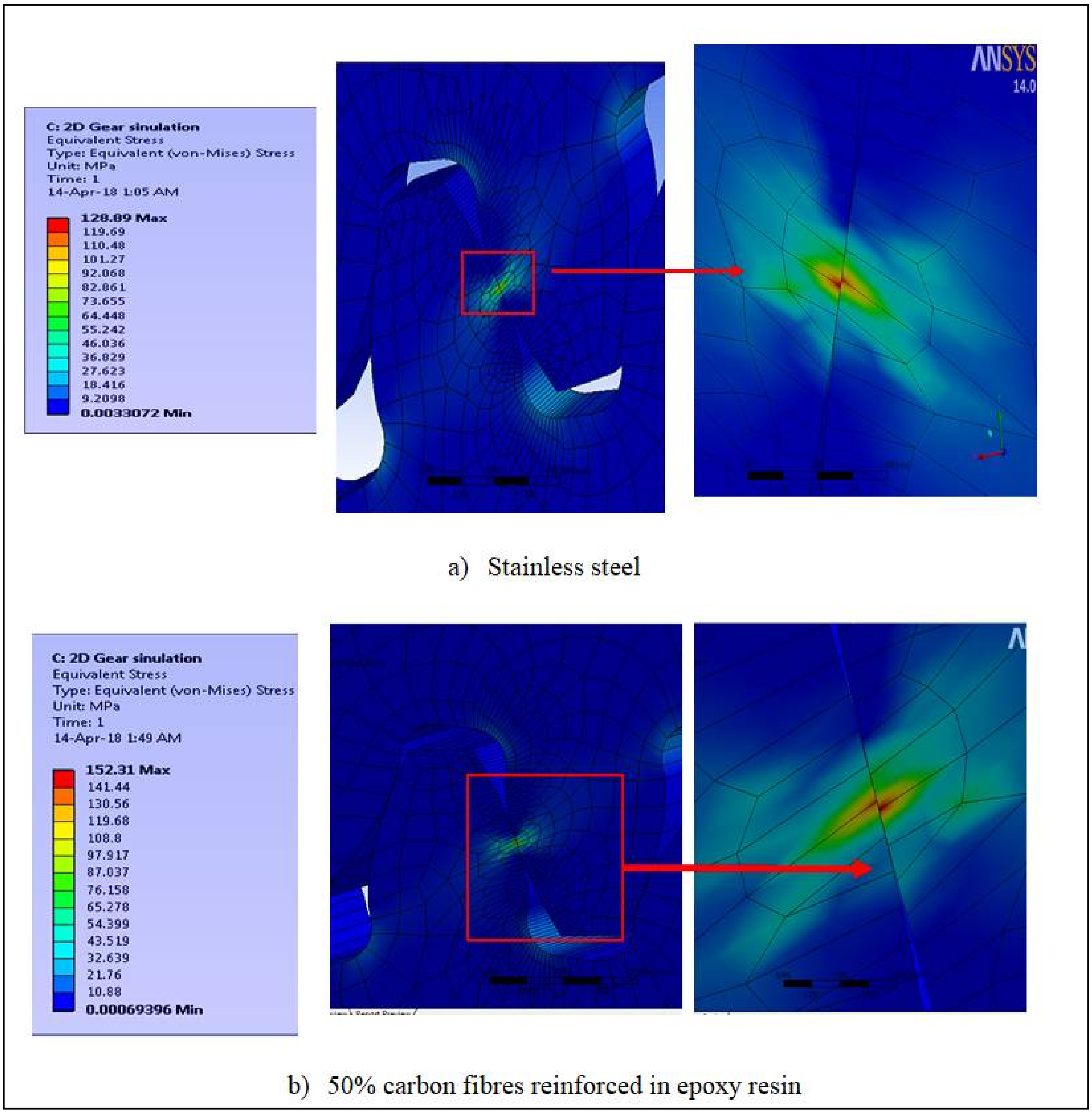

Figure 6: Von-Mises stress distribution for(a steel and b) 50% carbon fibres reinforced in epoxy resin

The von Mises strain study was also numerically done for different spur gear materials. Figure 7 A and B compares the strain distribution and maximum von-Mises strain for stainless steel and 50% carbon fibers reinforced in epoxy resin, respectively. Whereas for other materials like copper alloy, 1.5 percent filler contained acetal, and glass-filled polyamide, only the maximum. Minimum values were mentioned in this paper (se Table 3). As a result, the maximum strain of steel is around 67×10^{-5}, whereas the maximum strain of 50% carbon fibers reinforced with epoxy resin is roughly 36×10^{-5}. The maximum strain in the other materials is as follows: copper alloy has a strain of 10×10^{-4}, 1.5 percent filler containing acetal has a strain of 10×10^{-3}, and glass filled polyamide has a strain of 74×10^{-4}.

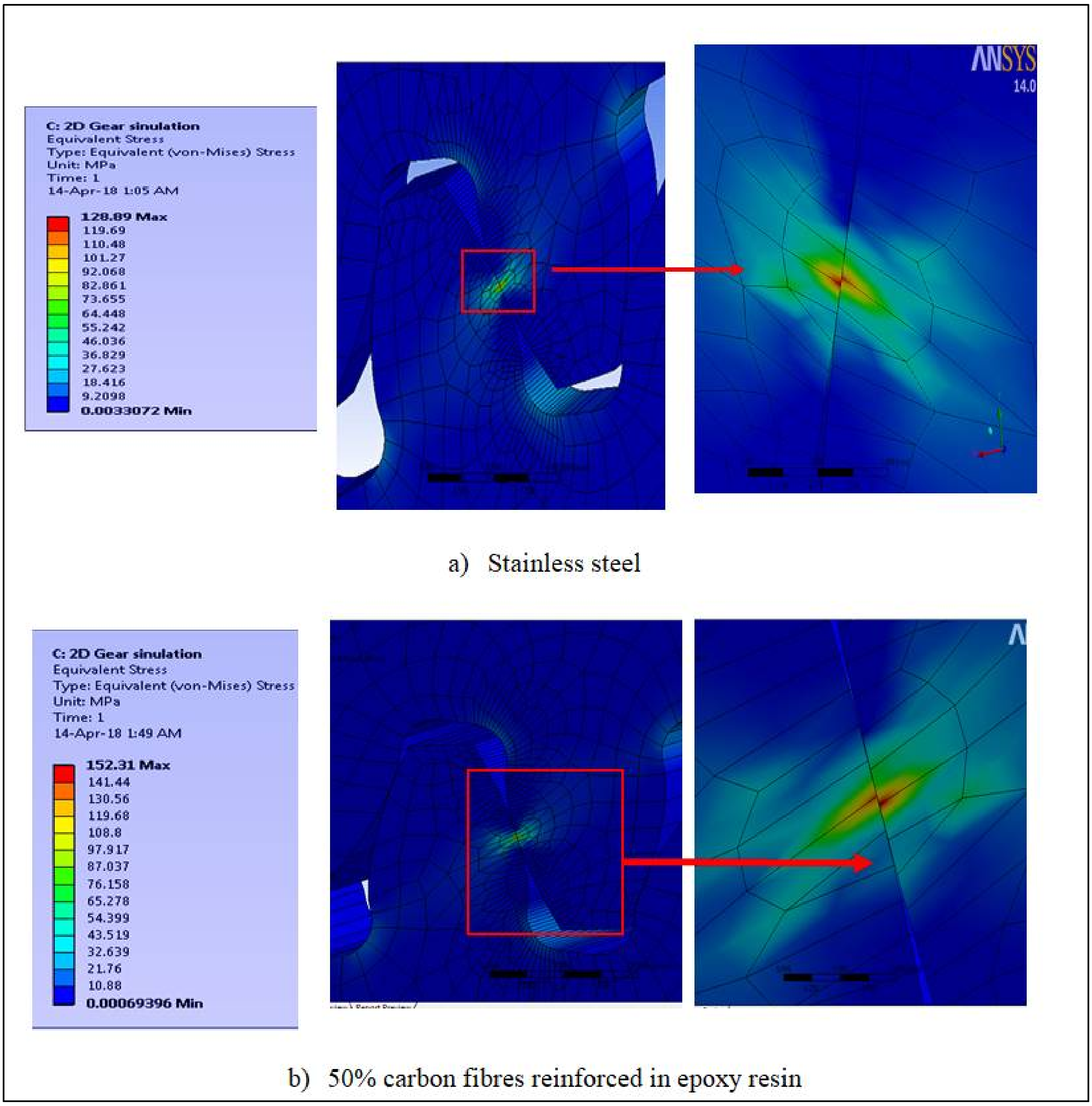

Figure 7: Von-Mises strain distribution for (a steel and b) 50% carbon fibres reinforced in epoxy resin

Table 3 summarizes the findings of the correlational maximum allowable contact stress between two spur gears for conventional and composite materials, using both the Hertzian contact and ANSYS methods. Compared to others, this finding is consistent with that of [9], who found that the contact stress for both methods was comparable. It can be seen from the data in Table 3 that the Hertzian contact stress for the first three materials was reported significantly more than the ANSYS contact stresses, while this result for the other two materials was less. What is interesting about the data in Table 3 is that the results for all materials, except 50% carbon fibers reinforced in the epoxy resin matrix, were very close to each other. These results are consistent with the trends reported by some researchers [7, 9, 19, 22].

The next section of ANSYS results in Table 3 concerning total deformation, which was analyzed using ANSYS workbench 14.0 under the same conditions of torque (63662 *N-mm*) and rotational speed of (1500 *RPM*). Furthermore, closer inspection of Table 3 shows that the maximum deformation was reported for 1.5% filler contained acetal by 0.050139 *mm*. In contrast, 50% carbon epoxy was deformed at a minimum value of 49×10^{-5} *mm* compared to other materials. According to the investigation's findings, the deformation of 50% carbon fibres reinforced in an epoxy resin matrix is relatively minor compared to the other materials. As a result, it is concluded that carbon fibers in an epoxy resin matrix are a better alternative to steel. This finding was also reported by Devi [19].

Table 3: Spur gear analysis results

	Hertzian		ANSYS	
Materials	***Contact stress (MPa)***	***Von-Mises Stress (MPa)***	***Equivalent elastic strain***	***Directional deformation (mm)***
Stainless Steel	165.53	128.89	0.000676646	0.0012066
Copper Alloy	127.12	117.12	0.0010868	0.021196
50% Carbon fibers reinforced in epoxy resin	250.13	152.13	0.00036241	0.00049012
1.5% Filler Contained Acetal	21.644	33.017	0.010678	0.050139
Glass Filled Polyamide	28.9	44.916	0.0074312	0.026204

Figure 8 compares the contact stress of numerical and Hertzian analysis for different materials in bar chart form. The most interesting aspect of this graph is that no significant difference in the number of stainless steels, copper Alloy, 1.5% filler contained acetal, and glass-filled polyamide was detected when Hertzian contact stress was stimulated with ANSYS contact stress. This study supports evidence from previous observations (e.g., Nikhil *et al*. [5]; Gupta *et al.* [7]; Mounika *et al.* [23]). There was a significant difference between the two methods when 50% carbon fibers reinforced in epoxy resin matrix were used, which is Hertzian analysis was 250.13 MPa. In contrast, this result was reduced up to 152.13 MPa in FEM. However, in reviewing the literature, no data was found on the association between Hertzian contact stress and ANSYS contact stress analysis for stainless steel, copper alloy, 1.5% filler contained acetal, and glass-filled polyamide.

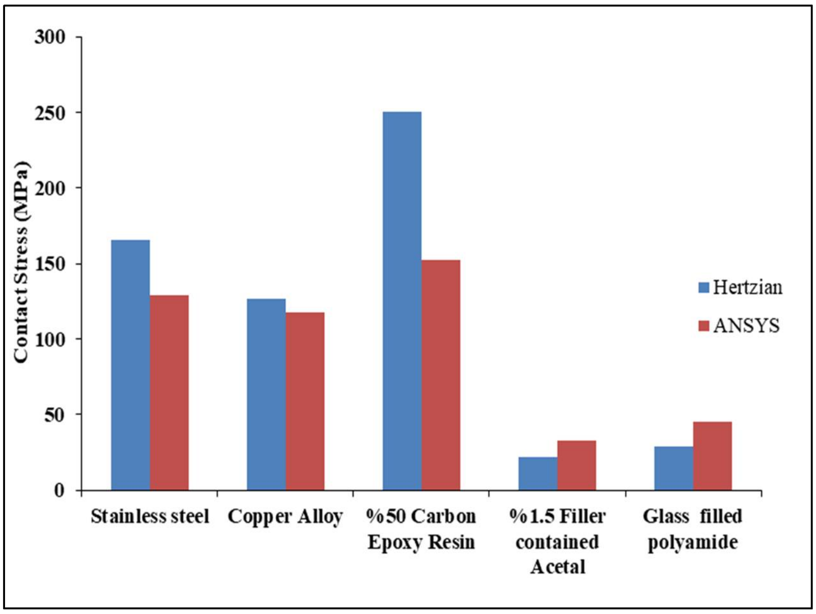

Figure 8: The relation between contact stress in Hertzian and FEM (ANSYS)

Overall, the current study found that 50% carbon fibers reinforced in the epoxy resin matrix was the best material in which the spur gear material could be replaced by 50% carbon fibers reinforced in the epoxy resin matrix. This is due to its low density, lower deformation, and high strength.

In future investigations, it might be possible to use a different spur gear analysis that identifies the bending stress, changing power, speed, and load.

5. Conclusion

In this study, five different materials, including two conventional and three composite materials, have been investigated using two different methods: ANSYS and Hertzian contact. The main goal of the current study was to determine the optimal material for the spur gear, considering the weight and strength. The results of this investigation showed that:

1) The spur gear made from carbon fibers in an epoxy resin matrix has more contact strength than the other spur gear materials.
2) Compared to other spur gear materials, 50% carbon fibers reinforced with epoxy resin deformation is quite low.
3) Therefore, the spur gear material may be replaced with carbon fibers in an epoxy resin matrix, resulting in high strength, low weight, and noise-free motion, increasing the system's overall mechanical efficiency.

The study is limited by the lack of information on bending stress. In addition, there are many unanswered questions about spur gears in different materials, for instance, changing the rotational speed, transmitting power, gear dimensions, etc. Therefore, further studies, which take these variables into account, will need to be undertaken, and this would be a fruitful area for further work.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

Nomenclature

P	Maximum pressure (N)	F_t	Tangential component of the resultant force (N)
F	Force pressing the two cylinders together (N)	T	Transmitted torque (N-mm)
b	Half width of deformation (mm)	n_p	Rotational speed (RPM)
L	Face width (mm)	SF	Safety factor
d	Diameter of cylinder (mm)		
E	Modulus of elasticity (N/mm^2)	**Greek Symbols**	
d_{pp}	Pitch circle diameter of pinion (mm)	ϕ	Pressure angle
d_{pg}	Pitch circle diameter of gear (mm)	v	Poisson's ratio
d_p	Pitch circle diameter (mm)	σ_{ca}	Maximum allowable stress (MPa)

[1] N. D. Narayankar and K. S. Mangrulkar, Contact Stress and Bending Stress Analysis of Spur Gear by Analytical Method, Int. J. Theor. Appl. Res. Mech. Eng., 6 (2017) 1–2.

[2] A. Gopi chand, A. V. N. L. Sharma, K. P. Kumar, K. Sainath, and I. Aravind, Design of Spur Gear and its Tooth profile, Int. J. Eng. Res. Appl., 2 (2012) 820–827.

[3] S. Damtie and T. Daniel, Contact Stress Analysis of Involute Spur Gear by Finite Element Method (FEM), Zede J., 32 (2014).

[4] M. P. Chor and P. Pillai, Spur Gear Contact Stress Analysis and Stress Reduction by Experiment Method, Int. J. Eng. Res. Gen. Sci., 3 (2015).

[5] B. A. Nikhil, M. M. Mirza, and P. V. Pawar, Effect of Change of Spur Gear Tooth Parameter On Contact stress, Int. Res. J. Eng. Technol., 4 (2017) 1259–1263.

[6] S. P. Rao, N. Sriraj and M. Farookh, Contact Stress Analysis of Spur Gear for Different Materials using ANSYS and Hertz Equation, Int. J. Mod. Stud. Mech. Eng., 1 (2015) 45–52.

[7] B. Gupta, A. Choubey, and G. V. Varde, Contact Stress Analysis of Spur Gear, Int. J. Eng. Res. Technol.,1 (2012).

[8] N. Kapoor, V. Upneja, R. Bhool, and P. Katyal, Design and Stress Strain Analysis of Composite Differential Gear Box, Int. J. Sci. Eng. Technol. Res., 3 (2014) 1881–1895.

[9] [Shanavas., Stress Analysis of Composite Spur Gear, Int. J. Eng. Res. Technol., 2 (2013) 38–43.

[10] S. Mahendran, K. M. Eazhil, and L. S. Kumar, Design and Analysis of Composite Spur Gear, Int. J. Res. Sci. Innov., 1 (2014).

[11] A. Nath and A. . Nayak, Design and Analysis of the Composite Spur Gear, Int. J. Adv. Technol. Eng. Sci., (3) 2015.

[12] S. Arunkuma, S. Easwaran, B. Murugan, B. Prathess, and K. Vediyappan, Design and Stress, Strain Analysis of Polyoxymethylene Spur Gear for Sugarcane Juice Machine, Int. J. Res. Aeronaut. Mech. Eng., 3 (2015) 69–81.

[13] P. B. Pawar and A. A. Utpat, Analysis of Composite Material Spur Gear under Static Loading Condition, Mater. Today Proc., 2 (2015) 2968–2974. https://doi.org/10.1016/j.matpr.2015.07.278

[14] A. C. Dhomse and R. K. Agrawal, Design and Analysis of Polymer PEK Spur Gear under Static Loading Condition Using FEA, Int. J. Innov. Res. Sci. Eng. Technol., 5 (2016) 1463–1468.

[15] H. P. Rahate and R. A. Marne, Finite Element Analysis of Composite Spur Gear for Contact Stress, Int. Conf. Recent Res. Dev. Sci. Eng. Manag., (2016) 226–231.

[16] M. Singh, W. Khan, and S. Kumar, Structural Analysis of Composite Material Helical Gear under Different Loading Condition, Int. J. Eng. Sci. Res. Technol., 5 (2016). https://doi.org/10.5281/zenodo.55629

[17] S. Rajeshkumar and R. Manoharan, Design and analysis of composite spur gears using finite element method, IOP Conf. Ser. Mater. Sci. Eng., 263 (2017). https://doi.org/10.1088/1757-899X/263/6/062048

[18] S. Ramanjaneyulu, K. N. S. Suman, S. Phani Kumar, and V. Suresh Babu, Design and Development of Graphene reinforced Acetal copolymer plastic gears and its performance evaluation, Mater. Today Proc., 4 (2017) 8678–8687. https://doi.org/10.1016/j.matpr.2017.07.216

[19] S. K. Devi, Finite Element Analysis of Composite Spur Gear, J. Mech. Civ. Eng., 3 (2017) 13–16.

[20] M. J. Khan, A. Mangla, and H. Din, Contact Stress Analysis of Stainless Steel Spur Gears using Finite Element Analysis and Comparison with Theoretical Results using Hertz Theory, M Jebran Khan al. Int. J. Eng. Res. Appl., 5 (2015) 10–18.

[21] M. Li and S. J. Zinkle, Physical and Mechanical Properties of Copper and Copper Alloys, 2012.

[22] W. J. Qin and C. Y. Guan, An investigation of contact stresses and crack initiation in spur gears based on finite element dynamics analysis, Int. J. Mech. Sci., 83 (2014) 96–103. https://doi.org/10.1016/j.ijmecsci.2014.03.035

[23] S. S. Mounika, Contact Stress Analysis of Spur Gear for different Materials using Ansys and Hertz Equation, Int. J. Res. Appl. Sci. Eng. Technol., 7 (2019) 1077–1082. https://doi.org/10.22214/ijraset.2019.7175