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Contact stress analysis of steel and composite spur gear pairs

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Abstract

Gears are one of the most critical components in a mechanical power transmission system and in most rotating machinery. Gear teeth usually fail due to increase in load above certain limit. Therefore, it is required to use different materials for gear manufacturing. Metal matrix composites possess improved properties including high strength, high stiffness, and reduction in weight, compared with unreinforced alloy. The objective of this work is concerned with replacing metallic gear with gear of composite material of aluminium silicon carbide and fly ash so as to improve performance of machines and to have longer working life. Aluminium alloy, SiC and fly ash are used as matrix and reinforcing material. Contact stress is the key parameter in mating gear in gear design. This work represents contact stress analysis of steel and composite gear pairs using hertz theory and finite element analysis (FEA) using ANSYS. In this work, aluminium silicon carbide and fly ash is used as a gear material. Also experimental stresses are calculated using strain gauge technique. When compared, the results of both theoretical method and FEA show a good degree of agreement with experimental results. It is observed that stresses are nearly reduced by 18% by the use of composite material. Also the weight of composite material is nearly 3 times less than steel material. So the composites can be used for making power transmitting elements such as gears, which are subjected to continuous loading.

Keywords

Contact stress, Hertz equation, Spur gear, Composite gear, ANSYS 16.0, Strain gauge.

1.Introduction

Aluminium alloy materials or simply metal matrix composites are combinations of materials. Composites are made up of combining two or more materials in such a way that the resulting materials have certain design properties or improved properties. Aluminium alloy composite materials are mostly used for a many number of applications such as engineering structures, electronic applications, sporting goods as they are less in weight with better properties [1].

Gears are the most common method of transmitting power in mechanical engineering. With the moving wheel of science and technology the use of gears has become preferably common in almost all the upcoming industries. The spur gear are simple in design, manufactured economically, requires less maintenance. Fly ash, borax powder or magnesium is added to improve the properties [2]. In present work the main objective is to replace metallic gear with gear of composite material of aluminium silicon carbide and fly ash so as to improve performance of machine and to have longer working life.

The objectives of this paper are as follows:

1. To design and analyze the gear using computer-aided design (CAD) and computer-aided engineering (CAE) software.
2. To increase the contact strength of spur gear using composite material.
3. To determine the contact stress by using strain gauge setup.

2.Literature review

Pawar and Utpat [1] have developed a metal matrix composite of aluminium based silicon carbide. Authors has done FEA of gear using ANSYS 14.0 and concluded that composite gears offer improved properties over steel alloys and can be replaced with metallic gears [2]. Saravanan and Kumar[3] has developed metal matrix composites by varying rice husk ash percentage and concludes that with increase in percentage of rice husk ash in metal matrix composites will increase ultimate tensile strength, compressive strength and hardness of the composite. Devi et al. [4] conducted experiments for tensile strength by varying mass fraction of SiC with aluminium and found that aluminium silicon carbide composite material is having less weight and more

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strength. Suragimath and Purohit [5] conducted experiment by varying fly ash weight fraction with constant SiC and found that the increase in addition of fly ash increases the tensile strength, impact strength, wear resistance of the specimen and decreases the percentage of elongation.

Hassan [6] considered different contact positions for contact stress analysis between two spur gear teeth, representing a pair of mating gears during rotation and developed a programme to plot a pair of teeth in contact. Hwang et al. [7] presents a contact stress analysis for a pair of mating gears during rotation and performed contact stress analysis for spur and helical gears between two gear teeth at different contact positions during rotation.

Tiwari and Joshi [8] presented analysis of bending stress and contact stress of involute spur gear teeth and found that hertz theory is the basis of contact stress calculation. Theoretical results which are obtained from Lewis formula and Hertz equation are comparable with FEA results. Khan and Mangla [9] analysed contact stress of spur gears by theoretical method using Hertz equations and by FEA using ANSYS 14.0 workbench. The spur gear is sketched, modelled and analysed using ANSYS. It is found that the results obtained from theoretical method and FEA are comparable with each other.

Quadri and Dhananjay [10] Analysed spur gear pair for contact stress analysis which is under static loading conditions. The results obtained for contact stresses using Hertz theory and FEA are compared. Kolambe and Barde [11] analysed helical gear using FEA. To calculate the bending stress, 3D solid models for different number of teeth are generated by using CATIA and the numerical analysis is done by FEA using ANSYS. The Lewis stress formula is used for analytical investigation. The stresses found by using ANSYS are compared with results obtained from theoretical and AGMA values. Rahate and Marne [12] conducted FEA for contact stress analysis on composite spur gear pair and found that stress is reduced due to use of composite gear.

Patil et al. [13] studied contact stress in gears. Gear dynamic stress test rig (GDSTR) is used for experimental testing and analysis of the helical gear. The strain gauge and carbon slip rings are used in GDSTR to measure the surface contact stresses at the contacting points of a meshed gears. Jebur et al. [14] investigates the characteristics of an Involute gear system including contact stresses between pair of the gears for 3D and comparing the results with the experimental results. The experimental analysis established in new idea by using the D.C servomotor and planting the strain gauges in the tooth of the gear. Chor and Pillai [15] studied gear by increasing the module of gear to reduce contact stress. One spur gear train is selected for analysis. The contact stress of already existing gear train is determined and compared with fatigue strengths of gear material. If these calculated stresses on gears higher than fatigue strengths then it means gears are failed due to fatigue. The contact stress is calculated by using Hertz's equation and the experimental investigation of the stress field is done by using strain gauge technique.

3.Material properties and design parameters

For investigation, Al, SiC (12%), fly ash (15%) is used as a matrix material. The material properties of steel and aluminium silicon carbide composite are given in the *Table 1*.

The basic design of spur gear is same for both the gears as the comparative study of steel gear and composite gear is done. The various parameters of gear design are given in the *Table 2*.

Table 1 Material property of gears

Material properties	**Steel**	**AlSiC + FA**
Young's modulus	200 GPa	134 GPa
Poisson's ratio	0.3	0.29
Ultimate tensile strength	841 N/mm^2	402 N/mm^2
Density	7850 Kg/m^3	2580 Kg/m^3

Table 2 Design parameters of gears

Parameters	**Value**
No. of teeth	20
Module	4.5 mm

Parameters	Value
Gear ratio	1
Pressure angle	20^0
Face width	30 mm
Center distance	90 mm
Pitch diameter	90 mm
Torque	150 m

4.Theoretical contact stress analysis using hertz theory

Earle Buckingham have used hertz theory to calculate contact stresses between rotating pair of teeth in 1926 by considering external cylindrical spur gears as two parallel cylinders in contact with radiuses of curvature. When two cylinders are pressed together then the contact stress is given by [16],

$$\sigma_c = \frac{2P}{\pi BL} \quad (1)$$

$$B = \left[\frac{2P\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)}{\pi L\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}\right]^{1/2} \quad (2)$$

Where,

- σ_c = maximum value of contact stress in N/mm^2
- P = force pressing the two cylinders together in N
- B = half width of deformation in mm
- L = axial length of cylinders in mm
- d_1 ,d_2 = diameters of two cylinders in mm
- E_1,E_2 = modulii of elasticity of two cylinder materials in N/mm^2
- μ_1,μ_2 = Poisson's ratio of the two cylinder materials

Substituting value of half width of deformation, B in equation (1) and squaring both sides,

$$\sigma_c^2 = \frac{1}{\pi}\left(\frac{P}{L}\right)\left[\frac{\left(\frac{1}{r_1}+\frac{1}{r_2}\right)}{\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)}\right] \quad (3)$$

If it is assumed that the material of both the cylinders is same, then the modulus of elasticity and Poisson's ratio will be same. Therefore, substituting E_1=E_2=E and μ_1=μ_2=μ in equation (4),

$$\sigma_c^2 = \frac{1}{2\pi}\left(\frac{P}{L}\right)\left[\frac{\left(\frac{1}{r_1}+\frac{1}{r_2}\right)}{\left(\frac{1-\mu^2}{E}\right)}\right] \quad (4)$$

Now, to apply this equation to a pair of spur gear teeth in contact, it is necessary to replace the radii r_1 and r_2 by the radii of curvature at the pitch point,

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

Now, since the pinion and gear are of equal geometry as given in *Table 2*, then

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

$$r_1 = r_2 = r = \frac{d_p sin\phi}{2} \quad (5)$$

From equation (4) and (5),

$$\sigma_c^2 = \frac{1}{\pi(1-\mu^2)}\left(\frac{PE}{Lr}\right) \quad (6)$$

now,

$$r = r_p sin\phi \text{ and } P = \frac{P_t}{cos\phi}$$

The tangential force acting on the tooth can be calculated by,

$$P_t = \frac{2T}{d_p}$$

The length *L* and face width *b* of spur gears are considered as same, therefore replacing *L* by *b* in equation (6). Then the equation is obtained as,

$$\sigma_c = \left[\frac{1}{\pi(1-\mu^2)}\left(\frac{P_t E}{b r_p sin\phi cos\phi}\right)\right]^{1/2} \quad (7)$$

By using equation (7) theoretical contact stress can be calculated.

Table 3 shows theoretical contact stresses in steel and composite gear using Hertz equation.

Table 3 Theoretical data for contact stress in steel and composite gear using Hertz equation

Torque (N.m)	Tangential force (N)	Contact stress in steel gears (MPa)	Contact stress in composite gears (MPa)
50	1111.11	423.26	345.34
100	2222.22	598.59	488.38
150	3333.33	733.12	598.14

5.Numerical analysis using FEA

In the present study, FEA software ANSYS 16.0 workbench has been used for numerical analysis to calculate the maximum allowable contact stress in steel and composite spur gears. The gear is modelled in CREO 3.0 and imported in ANSYS as STP file for analysis. Fine meshing has been done as shown in *Figure 1*, in order to get good results. Fixed support is applied on inner rim of the gear. Frictionless support is applied on the inner rim of other gear to allow its tangential rotation [17]. A moment of 150 N.m is applied in clockwise direction on the inner rim of the gear as shown in *Figure 2*.

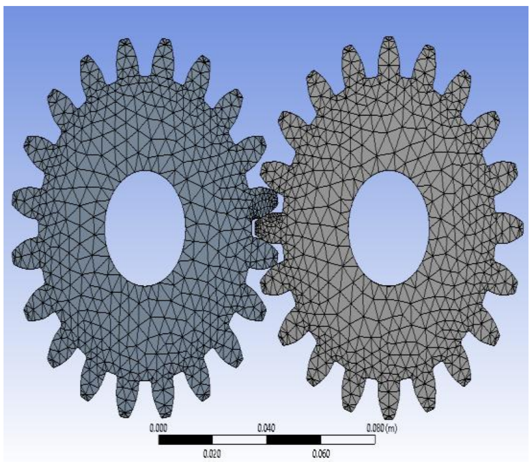

Figure 1 Meshed model

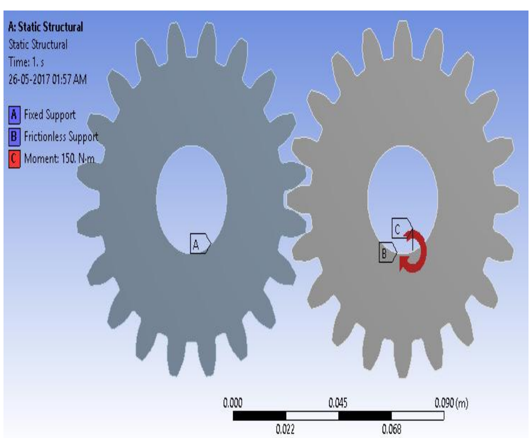

Figure 2 Boundary conditions

Figure 3 shows the maximum contact stress obtained for steel gear pair for 150 N.m torque. The finite element analysis is done by using ANSYS.

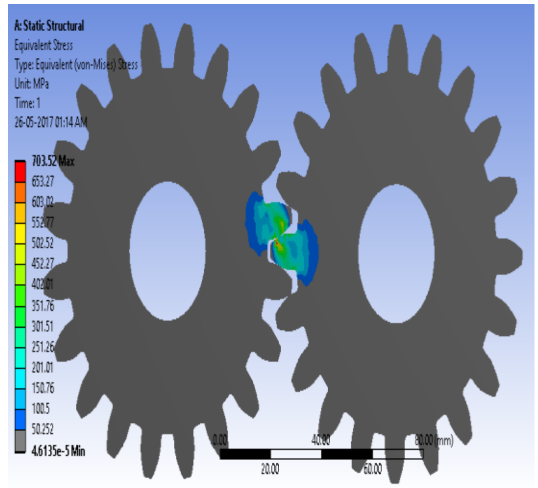

Figure 3 Contact stress of steel gear pair for 150 N.m torque

Figure 4 shows the maximum contact stress obtained for composite gear pair for 150 N.m torque. The finite element analysis is done by using ANSYS.

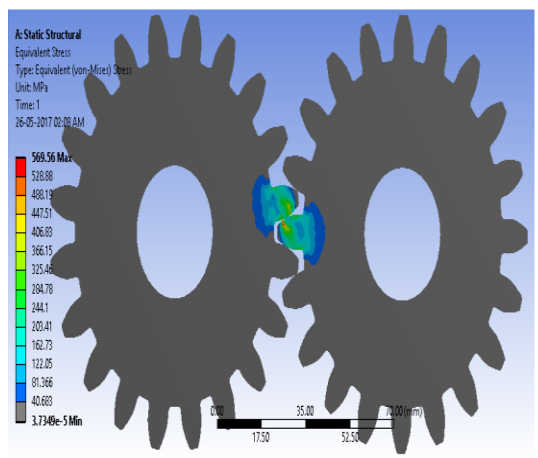

Figure 4 Contact stress of composite gear pair for 150 N.m torque

Table 4 shows contact stresses calculated using FEM for steel and composite gear.

Table 4 FEM data for contact stress in steel and composite gear

Torque (N.m)	Tangential force (N)	Contact stress in steel gears (MPa)	Contact stress in composite gears (MPa)
50	1111.11	398.70	331.23
100	2222.22	564.32	460.04
150	3333.33	703.52	569.56

6.Experimental stress analysis using strain gauge technique

The experimental stress analysis is carried out by using strain gauge technique. Strain gauges are planted on the gear tooth faces. Strain gauges with Wheatstone bridge circuit are used to find strain values. By using experimental strain, stresses can be calculated.

Figure 5 Loading arrangement of gear pair

Table 5 and *Table 6* shows contact stresses calculated using experimental strain gauge technique.

Table 5 Experimental data for pair of steel gear

Load (Kg)	Torque (N.m)	Tangential force (N)	Experimental strain (μe)	Contact stress (MPa)
5	50	1111.11	0.002260	452.12
10	100	2222.22	0.003239	647.85
15	150	3333.33	0.004	800

Table 6 Experimental data for pair of composite gear

Load (Kg)	Torque (N.m)	Tangential force (N)	Experimental strain (μe)	Contact stress (MPa)
5	50	1111.11	0.002792	374.34
10	100	2222.22	0.004	536
15	150	3333.33	0.004872	652.87

7.Result and discussion

In this work, the contact stresses in the gears are calculated by Hertz theory and FEM. It is validated by conducting the experiment using strain gauge technique. *Figure 6 and Figure 7* shows the comparison of stresses obtained with FEM, Hertz theory and experimental method. It shows good level of agreement by all the method.

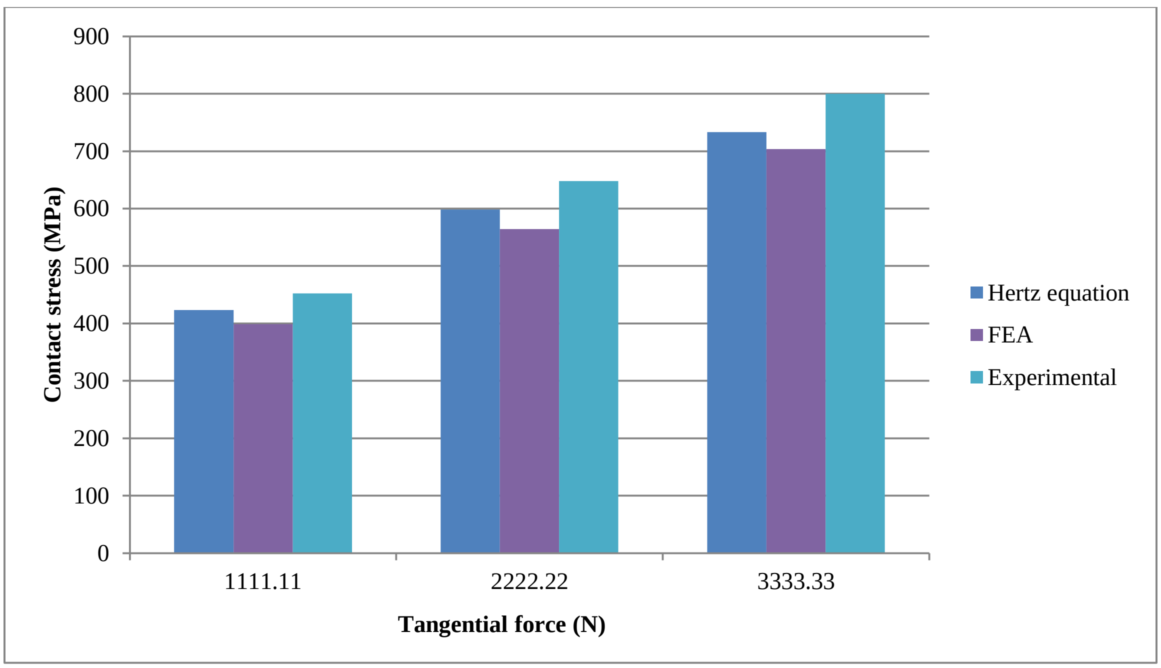

Figure 6 Plot of contact stress vs tangential force for steel gear pair using Hertz equation, FEA and Experimental

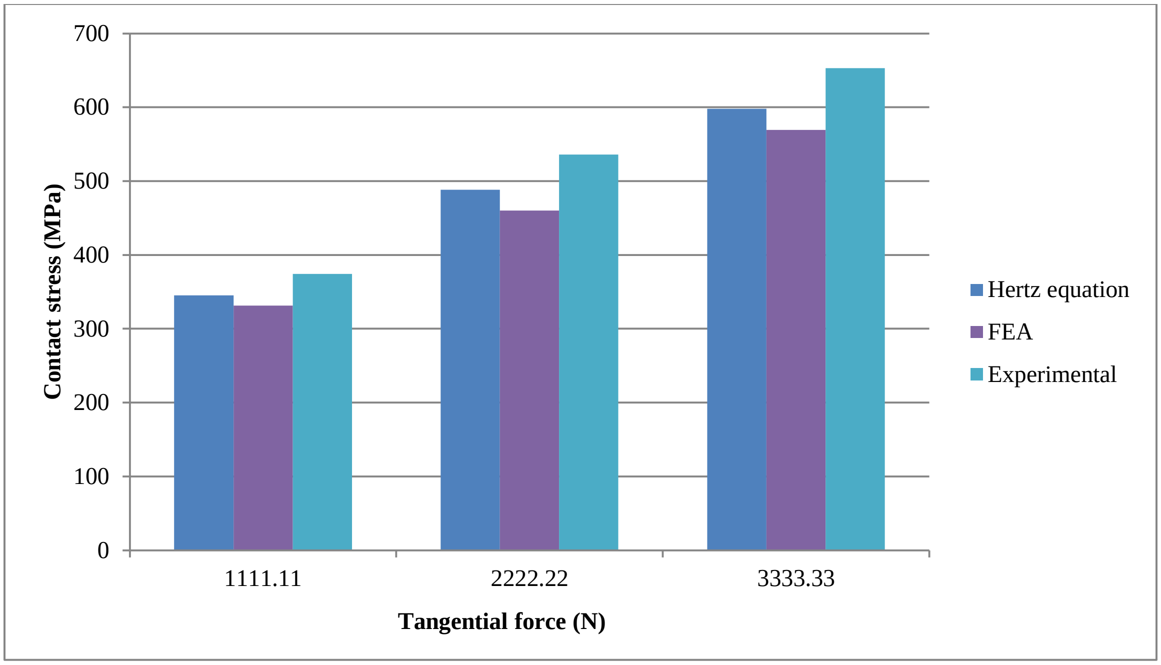

Figure 7 Plot of contact stress vs tangential force for composite gear pair using Hertz equation, FEA and Experimental

Percentage difference of stresses for steel and composite material using analytical method, FEA and experimental method is calculated. It is observed that the stresses are reduced by nearly 18% due to the use of composite material. Also the results are well within the difference of 10 %.

8.Conclusions and future scope

The following conclusions has been drawn from present study:

1. The density of composite gear is 2580 kg/m^3 as compared to 7850 Kg/m^3 of steel gear. Thus the weight is reduced by almost 3 times by the use of composite gears.
2. The Aluminium silicon carbide and fly ash composite material is having less weight and more strength; It is very much useful in practical aerospace applications.
3. It was found that the results from both Hertz equation and FEA are comparable with the experimental strain gauge technique. The results are well within the difference of 10%.
4. It was found that the results from Finite Element Analysis are comparable with the experimental Strain gauge technique. The results are well within the difference of 15%.
5. It is observed that stress is reduced by nearly 18% due to the use of composite material.
6. These composites can be used for making power transmitting elements such as gears, which are subjected to continuous loading.

In future, this work can be extended by doing modal analysis of composite gears. Also vibration analysis can be done to check the effect of material. This work can be extended for analysis of bending strength of composite gear.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

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