Experimental and analytical stress analysis of spur gear

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Abstract: Gears are most powerful machine element to transmit the motion between rotating shaft. It acts as a dominating transmission system from many years ago. In this work, a spur gear from stone crusher machine is analysed using theoretical Lewis equation and Finite element analysis method. Here, the bending stress on the spur gear is analysed since these stresses induced play a vital role in gear life. The analysis presented the effect of gear material on induced bending stress. The material C15 steel/CI 30 is replaced by C45 steel/CI 30. The C45 steel material has better mechanical properties than C15 material. The result explains that C45/CI30 gives lower value of bending stress as compare to the existing material. Module is important parameter during modelling of spur gear. The parameter is varied and proportionally the bending stress are determined theoretically for both new and existing materials. Finally the results of both gear are compared and concluded with the American gear manufacturer association data. The results shows that the bending stress reduces with increase in module. The future work is to find the bending stress induced on spur gear by varying the module using FEA and varying the shape of meshing structure.

1. Introduction

Gear is a mechanical element used to transmit power and motion by progressively engagement of teeth. By employing belt drive, chain drive and other method of power transmissions slipping occurs and require greater space requirement. To overcome the problem of slipping and compactness, gears are employed which produce a positive drive with uniform angular velocity. The main objective of gear drive system is to transmit high power with smaller dimension of driving system which can be fabricated with minimum manufacturing cost and runs free of vibration and noise. So design should economically sound and feasible. Finite Element Analysis is a numerical method of for solving many complex real life system in engineering disciplines. It is a powerful tool for engineering analysis to solve structural, biomechanics, electromagnetic field, linear static and nonlinear transient dynamic problem. FEA works with different levels of geometry idealization and gives results with better accuracy. In recent trends, designing of gear becomes a highly complicated subject in the area of machine design. So, it must be accurate and rugged.

There are several types of gear available but the simplest and widely used gears are the one which used to transmit determined speed ratio between two parallel shafts at defined distance spur gear is
type of gear in which teeth are straight and are parallel to the wheel axis. Here parallel and co-planar shafts are used to connect the gear. Such arrangement is referred as spur gear. The merits of spur gear are easy to design, low maintenance and economical to manufacture and they impose only radial load on the bearings. Helical gears have their teeth inclined to the shaft axis which is in the form of a helix. These gears can carry high load compare to other gears. Single helical gears impose both radial loads and thrust loads on their bearings and so require the use of thrust bearings.

Bevel gears also called as Miter gears which are connected by intersecting coplanar shaft. Straight bevel gears can be used on shafts at any angle, but right angle is the most commonly used. The teeth of straight bevel gears are tapered in both thickness and tooth height. Worm gears are used to transmit power at right angle and employed where high speed reductions ratios are required. The shafts of worm gears lie in parallel planes and may be skewed at any angle between zero and a right angle. Worm gears are quiet, vibration free and give a smooth output. Worm gears and worm gear shafts are almost invariably at right angles.

Faydor Litvin et al.[1] investigated asymmetric modified spur gear drives. He developed geometry of gear drive to localize the contact of bearing. Then stress analysis of symmetric and asymmetric spur gear has performed. The result revealed that there is a reduction of bending and contact stress on an asymmetric spur gear. J. Andrew et al.[2] analysed using finite element method to determine fillet stress distribution. Here spur gear profiles of external and internal type are considered. The predicted results are compared with the photo elastic experiments. L. Fredette et al.[3] summarized reduction of stress in spur gear using stress relief feature. Here, holes were drilled on a part of gear especially in critical area to relief stress. Using finite element method, the stress was analysed by varying the hole size diameter. The obtained results were crosschecked by photo elastic testing method. V. Raja Prabhakaran et al.[4] analysed stress analysis of spur gear teeth. In this fatigue failure of tooth gear occurred due to repeating stress. Here different hole sizes are added on gear tooth at various location to reduce the concentration of stress. The result depicts that an aero shape fin type hole gives better results. Vivek Karaveeret al.[5] studied the modelling and finite element analysis of spur gear. He analysed the maximum contact stress in the mating spur gear teeth. Using finite element analysis this process is carried out and compared with theoretical models.

T. Veer Pratap Reddy et al.[6] investigated the contact pressure analysis of spur gear using finite element analysis. This paper explained the stress analysis on involute spur gear teeth. The results obtained by analytical method are compared with Hertz equation. The result conveys that as the module of gear increases the contact pressure decreases for a set of gears. Santosh Patilet al.[7] studied the contact stress analysis of helical gear in static condition. Here different angles of gear sets are employed. Using three-dimensional finite element analyses were carried out. The report conveyed that there is variation of contact stress with helix angle. The results are compared with theoretical data.

P. Ravikanth Raju et al.[8] studied using CAD and CAE modification of spur gear teeth. Here the strength of the gear tooth profile is improved by modifying the gear geometry. The gear tooth damaged is avoided by modification in root fillet. The modified teeth are compared with standard dimension. The result explained that circular root fillet type is better for lesser number of pinions.

Hariharan et al.[9] explained the spur gear tooth analysis to reduce the stress. Here different studies are carried out on contact point of gear tooth profile. The different stress relief feature is introduced in the gear geometry to find out the fatigue failure in gear. MS Hebbale et al.[10] analyses a study on reduction in fillet stress using stress relieving feature of various shape. Here a combination of circular and elliptical stress relief feature are introduced and result is summarized. The result obtain were better when compared to circular stress relief feature. Andrzej et al.[11] presented a comparative analysis of strength of tooth using ISO and AGMA standards. Here a model is developed and simulations are carried out using finite element methods. Different parameters are considered and analysis is carried out gives a data for modification of gear standards.

Seok et al.[12] summarized the contact stress analysis for a pair of mating gear during dynamic condition. Here spur and helical gear are investigated between two gear teeth at different point of contact during rotation. The results depict that contact stress on a gear set is more severe than AGMA standard. S. Vijayarangan et al.[13] studied
stress analysis of composite spur gear using finite element approach. Here static stress analyses are carried out on orthotropic material. The obtained results are compared with gear made of mild steel. The result confirmed that graphite epoxy composite gear gives better power transmission. Yogesh CHamand et al.[14] analysed stresses and deflection of sun gear by theoretical and ANSYS method. Here stresses on sun gear, deflection and various forces acting on gear tooth are analysed. The results obtained from ANSYS are compared with theoretical data. SPatilet al.[15] evaluated the contact pressure on a gear pair using finite element analysis. Here a model is created and studied is carried out along the line of action. The results are verified using twin disc experimental results and Hertz equation.

From, my above literature survey lot of research work are carried on stress analysis of spur gear and helical gear pair using theoretical Lewis equation and Finite element analysis method. The detailed study reports that analysis is done based on type of meshing shape, size and other parameters but there is very limited research work in replacement of material which is a greater research in field of science and technology. Hence, we have taken the spur gear pair from crushing machine and the design specification is analysed completely using Lewis equation method and bending stress are calculated as per loading condition. The replacement of material is done and dimension parameter is varied to analyse the bending stress induced in both existing and new designed spur gear.

2. Gear Materials
Materials play a tremendous role in designing the machine component. They are characterised by their properties. This property describe the material behaviour under the action of external load[16]. The stone crusher gear pair is selected for analysis purpose. Gear pair is made of pinion and wheel. The material involved in our study is C15 steel, C45 steel and cast iron grade 30. The three material differ by its mechanical properties. During selection, these mechanical properties play a vital role. The properties of materials are shown in Table 1 and dimension are listed in Table 2.

| Material property       | C15 steel | C45 steel | Cast iron 30 |
|------------------------|-----------|-----------|--------------|
| Poison's ratio         | 0.3       | 0.3       | 0.23         |
| Tensile strength(MPa)  | 490       | 700       | 300          |
| Yield strength(MPa)    | 240       | 360       | 200          |

Table 2. Gear dimension.

| Parameter               | Driving gear | Driven gear |
|-------------------------|--------------|-------------|
| Pressure angle (degree) | 20           | 20          |
| Number of teeth         | 18           | 45          |
| Module                  | 5            | 5           |
| Face width (mm)         | 47.25        | 47.25       |
| Root circle diameter (mm)| 77.5      | 212.5       |
| Tip diameter (mm)       | 100          | 235         |

3. Theoretical Analysis of Bending Stress
There are two major stresses developed during spur gear action. They are bending and contact stresses. The bending stresses are analysed theoretically by Lewis equation. In spur gear set a pinion gear is made of C15 steel and gear wheel is made of Cast iron grade 30. Here, theoretical calculation is performed for gear set. The data specification is obtained from spur gear pair in stone crusher application. From the data the speed of pinion gear is 900 rpm, power supplied is 2.5 kW, gear ratio is 2.5 and pressure angle is 20. The gear life of spur gear is 10000 hours.
\[ N = 1000 \times 60 \times 90 = 54 \times 10^7 \text{cycles} \]

The torque value is calculated for spur gear using

\begin{align*}
[M_r] &= M_t \times K \times K_d \\
[Ma] &= 238.73 Nm, K \times K_d = 1.3 \\
\text{Design torque}[M_d] &= 310.35 Nm
\end{align*}

According to Lewis bending equation the bending stress are given by

\[ \sigma_b = \frac{1.4 \times K_b l}{n \times K_b} \]

Where, \( K_{bl} = 1, n = 2, k_p = 1.2, \sigma_{bl} = 232.2 \text{N/mm}^2 \)

Design bending stress = 132.625 N/mm²

Now we going to find out the compressive stress using

\[ \sigma_c = CR \times HRC \times K_c l \]

Where, CR = 22, HRC = 63 for C15 steel, \( K_c l = 0.585 \), \( \sigma_c = 810.81 \text{N/mm}^2 \)

To determine the centre distance between gears

\[ a \geq (i + 1)^2 \sqrt{\frac{0.74^2 \times E_{eq} [M_t]}{\sigma_c^2 i \psi}} \]

Now we going to find out the compressive stress using

\[ \psi = b/a = 0.3 \]

\[ a = 136 \text{mm} \]

Let assume Number of teeth on pinion (Z1) is 18 and (Z2) is 45 and is calculated using \( Z_2 = i \times Z_1 \)

Then further the module is calculated and Centre distance is revised

\[ m = \frac{2a}{Z_1 + Z_2} \]

\[ m = 4.56 \text{mm} \]

Here we are determined the induced bending stress and compressive stress and compare the value with the allowable stress to check the design condition. Induced bending stress

\[ \sigma_b = \frac{(i + 1)}{amb} \]

\[ \sigma_b = 85.89 \text{N/mm}^2 \]

Design is safe that is \( \sigma_b < [\sigma_b] \)

Induced compressive from equation 3 is \( [\sigma_c] = 684.76 \text{N/mm}^2 \)

Design is safe that is \( \sigma_c < [\sigma_c] \)

For Cast iron grade 30 wheels and from Equation 2 the allowable bending stress is calculated for wheel,
From Equation 3 the allowable compressive stress is determined

\[ \sigma_{[\text{wheel}]} = \frac{1.4 \times K_H \times l}{n \times K_S \times \sigma_i} \]

\[ K_H = 0.918, \ n = 2, \ K_S = 0.45, \ \sigma_i = 130.5 \text{ N/mm}^2 \]

\[ \sigma_{[\text{wheel}]} = 69.88 \text{ N/mm}^2 \]

Therefore, induced bending stress on wheel is 68.75 N/mm² which is less than allowable bending stress on wheel. Hence design is safe.

4. Modelling

The sketch of 3D Spur gear and its assembly parts are shown in below figure.

![Figure 1](image)

**Figure 1.** (a) Three dimensional view of pinion and wheel (b) Three dimensional view of spur gear pair (c) Spur gear sketching.

5. Finite Element Analysis Using Ansys Work Bench

The spur gear of stone crusher machine is modelled in Creo. The assembled model which is saved in IGES format is imported to ANSYS workbench for static loading analysis. A frictionless support is
given at Centre face of pinion and wheel of spur gear and rotational speed of 900 rpm is applied on the pinion gear. The loading condition on assembled model is shown in Figure 4 and Figure 5 represents the meshed spur gear. The bodies of all spur gear are discretized in the form of tetrahedron shape meshing. A tetrahedron has 6 edges, 4 vertices, and is bounded by 4 triangular faces. The tetrahedral volume mesh can be generated automatically. This type of meshing gives more accurate results when compare to other meshing type. The loading condition are shown in Table 3.

| Gear material         | Rotation speed (rpm) | Support                                      |
|-----------------------|----------------------|----------------------------------------------|
| C15 Pinion/Castiron30 | 900                  | Frictionless support at centre face          |
| C45 Pinion/Castiron 30| 900                  | Frictionless support at centre face          |

**Table 3. Loading conditions.**

![Figure 2](image-url) **Figure 2.** (a) Loading condition (b) Meshing (c) Bending stress on C15 pinion gear (d) Bending stress on C45 pinion gear.
Here the spur gear made of C15 steel pinion and Castiron grade 30 are analysed for bending stress under static loading condition. The loading condition on the model is performed in ANSYS software. Meanwhile the material of the pinion is replaced by C45 steel. The results of both the analysed spur gear model are shown in Figure 6 and Figure 7 respectively. The stress distribution of the model will be displayed at left side of window. The colour range shows the maximum stress value to minimum stress value.

6. Results and Discussions
6.1 Replacement of Material.
Spur gear is made of small gear called pinion and bigger gear called wheel. Using Pro-E and Finite element analysis, a graph is plotted between induced bending stress and gear pair material. The maximum point of induced stress is 85 MPa in theoretical Lewis equation method and 73 MPa in Finite element analysis in existing design C15 steel/CI30. As the material is altered by replacing the pinion material by C45 steel. The result shows that the induced bending stress is 80 MPa by theoretical method and 70 MPa in the Finite element analysis method. The result explains that there is a reduction in induced bending in the new gear model. The results are plotted graphically and shown in below figure 8. The properties like yield strength, tensile strength, impact value, percentage of area reduction of C45 grade steel is better than C15 grade steel. Therefore, the material can withstand large amount of load with minimised bending stress and proportionally the wear reduces and life of teeth increases which drastically increase the product life and efficiency.

6.2 Module C15 Steel/CI30

Figure 3. (a) Material Replacement.

Figure 3. (b) Module C15 Steel/CI30.
6.2 Theoretical analysis of module in spur gear C15 steel/CI grade 30.
Module specifies the size of gear tooth. It is defined as pitch diameter to the number of teeth in spur gear. The results are plotted graphically and shown in figure 9. Here, the module are varied from 2, 3, 4, 5, 6 and 7. The induced bending stress are 1342 MPa, 397 MPa, 167 MPa, 85 MPa, 45 MPa and 31.03 MPa. The result shows that as the module increased the bending stress reduces. The induced theoretically stress is compared with American gear manufacturer association data. The results are nearly same with a small percentage difference.

6.3 Theoretical analysis of module in new design C45 steel/CI grade 30.
Here, the material is selected to overcome the properties of existing material. The selection depends on mechanical properties, cost and availability. Here, using theoretical Lewis equation method the module of spur gear is varied from 2, 3, 4, 5, 6 and 7 and induced bending stress is calculated. The induced stresses are 1330 MPa, 390 MPa, 164 MPa, 80 MPa, 40 MPa and 25 MPa. The result are compared with American gear manufacturer association bending stress value. The results are plotted graphically and shown in figure 10. From the graph the result shoes that as the module increases, the induced bending stress decrease when compare to the existing and new design for module 5 the bending stress is 80 MPa which is less than the existing design of same module. It shows that it gives better results than existing design.

7. Conclusions
Spur gear pair C15 Steel/CI30 and C45Steel /CI30 are modelled using Pro-E software. The induced bending stress and variation of parameter like module for both the gear pair are studied and analysed. The following conclusion are drawn from theoretical calculation and analysis.

- The bending stress induced in the spur gear pair C15/CI30 and C45/CI30 are analysed using theoretical Lewis equation method and Finite element analysis. C15 steel material is replaced by C45 grade steel to increase the life of product, and increasing the efficiency by reducing the bending stress induced at the mating point of gear teeth.
- The theoretical and analytical study of new design C45/CI30 shows the induced bending stress is reduced and material can carry large amount of load. Since, C45 grade steel has better mechanical properties than C15 steel.
- Module explains the gear tooth size. As the module increases, the size of gear tooth is reduced. Therefore, module is varied from 2, 3, 4, 5, 6 and 7 for both the spur gear design and induced bending stress is evaluated theoretical by Lewis equation method. The result shows that bending stress decrease with increase in module. Hence, higher modules can be suitable for large power transmission with minimum induced bending stress.
- Then the induced bending stress are compared with the American gear manufacturers association standard to obtained the standardized value against theoretical stress. The future work is to identify the bending stress value using Finite element analysis by varying the module.

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