COMPUTER AIDED DESIGN AND ANALYSIS OF PLAIN CARBON STEEL SPUR GEAR UNDER DIFFERENT FORCE APPLICATION

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Abstract: Effective power transmission in mechanical drive systems employs a gear as one of its foremost component. This is due to it suitability in compact transmission systems resulting from minimal center distance of mesh gear pair. In spur gear design the teeth profile and shaft axis to which the gear is fitted are parallel to each other. Spur gear is described as an uncomplicated type of gears and it is useful to transmit power linking parallel shafts. This paper communicates the design and analysis of plain carbon steel spur gear using SolidWorks. The Finite Element Method presented by the system is applied to analysis the design. In the present design, the approach is used to determine the minimum and maximum stresses, maximum displacement at the gear crown, deformation and the spur gear factor of safety for the applied forces; 400.34 N, 889.64 N and 1779.29 N, respectively. Simulation results indicate that with the present design; induced stress, displacement at the gear crown and deformation increases while factor of safety decreases. The maximum displacement for the gear occurs with the force application of 1779.29 N which is 1.36135 x 10^{-3} mm. Hence, for minimal induced stress at high force application a spur gear with improved material characteristics such as composite material is proposed.

Keywords: Computer aided design, finite element method, spur gear

Introduction

The manufacturing of any engineering product originates by the need of it application. Design and manufacturing processes are the two main processes undergone by any product from its commencement to the finished product. The design process (in further text design) entails the synthesis and analysis sub-processes (in further text analysis) (Zeid, 2004). Design and analysis are two important procedures in the product lifecycle of any engineering component.

Engineering drawing of a product showing structure of the product in different views with manufacturing details such as dimensions etc. form the basis of the product design. Previously, engineering drawing is been prepared manually by the draftsmen, but subsequent to the introduction of computer to engineering, engineering drawing has been prepared by CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) systems.

Analysis in contrast is the investigation of the engineering viability of the intended product design. It is a known fact that with the emerging complex structure of engineering product, manual analysis of product has become laborious.

The creation of computer models defined by geometrical parameters is implied to as Computer-Aided Design (CAD) (Zeid, 2004). These models are viewed on a computer screen as a three-dimensional (3D) representation of a part or system of parts, which can be effortlessly modified by changing relevant parameters. CAD systems permit designers to view objects in an extensive diversity of representations and assess these objects by simulating real-world conditions (Adekunle *et al*., 2015).

One of the worthy reasons for the development and application of CAD system is that it affords the prospect to develop the database needed to manufacture product (Adekunle & Adejuyigbe, 2012). The analysis of a product design is aimed at solving possible design problems which the new product is liable to and finding the best solution to these problems and making necessary adjustments. The analysis of a product design requires a geometrical model of the intended product and the simulation.

Simulation is described as the skill and discipline of creating an exemplification of a process or system (in this case the geometric model) for the intent of experimentation and evaluation (Martins *et al*., 2013). Similarly, simulation is explained as an approach to assist compress development cycle and help to achieve quick improvement and efficiency (Ayodeji *et al*., 2016). It is stated that the result of analysis is the design documentation in the form of engineering drawings.

The introduction of CAD/CAM systems as transformed the discipline of engineering; as once manually complex engineering drawings are now possible with CAD/CAM systems. Furthermore, various analyses and computation of interest can also be conducted on the model alongside creation of geometric model with CAD/CAM systems. Existing CAD/CAM systems (for example SolidWorks, Pro/E, and Parasolid) offers an array of engineering applications to execute various analyses on developed models such as mass property calculations, FEM and FEA (finite element modeling and analysis). The discussion in this paper is limited to design and analysis of plain carbon steel spur gear.

Gear Theory

Gear is an engineering component designed for efficient motion and power transmission in a compact mechanical assembly due to minimal center distance. A gear is described as a rotary cylinder-shaped wheel with tooth cut on it, the tooth engages another toothed part to transfer the power or torque (Karaveer *et al*., 2013). Gears has found it application in both small (wrist watch for example) and large (automobile transmission system for example) mechanism. The gear is said to be an essential machine component in mechanical power transmission system and most industrial rotary machinery (Dewanji, 2016; Mahendran *et al*., 2014). Spur gear, helical gear, worm gear and bevel gear are various kinds of gears commonly found in power transmission systems.

The choice of the kind of gear depends on some factors such as loading and speed. In spur gear design the teeth profile and shaft axis to which the gear is fitted are parallel to each other and are applied to transfer power between parallel shafts. Spur gear are said to give 98-99% operating efficiency (Karaveer *et al*., 2013).

Some basic terms and formulas in spur gear design are shown below (Khurmi & Gupta, 2005):

Diametral pitch *(P_d)*: a ratio of the number of teeth per inch of pitch diameter as Eq. (1):

$$P_d = \frac{N}{d} \tag{1}$$

Module *(m)*: ratio of pitch diameter to number of teeth as Eq. (2):

$$m = \frac{d}{N} \tag{2}$$

Circular pitch *(C_p)*: the measured distance along the circumference of the pitch diameter from the point of one tooth to the corresponding point on an adjacent tooth as Eq. (3):

$$C_p = \frac{\pi d}{N} = \pi m \tag{3}$$

Pitch diameter *(d)*: the diameter of the pitch circle from which the gear is design. This an imaginary circle, which will contact the pitch circle of another gear when in mesh as Eq. (4):

$$d = \frac{N}{P_d} = mN \tag{4}$$

Where *N* is the number of gear teeth

Motion and torque is transmitted in gear system when at least a pair of gear is in mesh. The minor of the meshing gears is implied to as pinion; the larger is implied to as the gear or the wheel (Shigley & Mischke, 1996).

In every pair of mesh gear, there is a driver and the driven. The speed (rpm) reduction and torque (Nm) increase or vise-versa between the driver and the driven gear depends on their gear ratio. One of the merits of gear application is it quiet power transmission which is a vital consideration in the design of vehicle and elevator gear systems for example.

Gear systems have high degree of reliability in power transmission and for this reasons it demand in such application is ever increasing. Consequent to this increase demand, the extensive analysis of gear at the design stage before manufacturing becomes an area of concern for many researchers in view of preventing possible failure. Gear analysis is of topmost significance in machine elements theory especially in the area of gear design and gear manufacturing (Bohidar *et al*., 2015).

The intent of analysis is to avert failure such as wear, scoring, interference, surface fatigue etc. Stress is one of the foremost failure factors in gear system. Stress occurs in gear as a result of contact between the gear teeth (meshing) of a pair of gear as power is been transmitted. This stress is implied to as contact stress and bending stress (Ganesh *et al*., 2015). These stresses cause fatigue and the union of both stresses results in failure of gear tooth and fracture at the tooth root.

Gear design optimization by analysis has been the rationale of much research. Several abstractions have been made by researchers in this area. Similarly, a number of literatures have been published on gear modeling. The gear stress analysis, bending stress and contact stress for gear sets in gear design are of core concern across the board of searched literature.

In the time past analysis in gear design is conducted analytically. This procedure is subjected to complicated calculations and hence laborious. The development and use of CAD/CAM systems has made the modeling and analysis of engineering entity computerized and more productive. The FEM and FEA is a common mechanical engineering numerical analysis technique use of engineering analysis on complex geometry and it is offered by most of the available CAD/CAM systems (SolidWorks for example)

Finite element method

The approach is known for its generality in solving engineering problems of any complicated shape or geometry (problem domain), material properties, boundary conditions, and loading conditions (Zeid, 2004). The pliability and diversity of FEM/FEA as an analyzing tool has made it generally accepted for engineering analysis in both engineering school and industries in recent time (Singh, et al., 2014). It is a known fact that it is difficult to obtain an exact closed-form solution via analytical mathematical method for all engineering problems; particularly with today's complex engineering designs. Hence, it is inevitable to obtain approximate solution to such problems.

The FEM/FEA has been to a large extent successful in the analysis of complex systems where closed-form solutions are either difficult or unavailable analytically. The initial step in using the method is the division of the complex shape (problem domain) into small elements. This is achieved by substituting the problem domain with a set of nodes properly connected to form the elements.

The finite element mesh is the assemblage of nodes and finite elements. The rule of thumb to element formations is that the more the number of element the more accurate the finite element solution (Zeid, 2004). However, the more pricey the solution; more memory space is needed to store the finite element model and more computer time is needed to obtain the solution.

FEM and FEA is capable of presenting information on contact and bending stresses in gears which has made the method popularly adopted by researchers to execute such analysis using compatible CAD/CAM systems. It is reported that FEA using appropriate CAD/CAM system can be used to compute the bending stresses in the gear tooth for given loading condition. Besides, stationary and dynamic loading conditions of the gear can equally be analyzed (Dewanji, 2016). The present work presents the design and structural (static) analysis of the performance of a plain carbon steel spur gear under different force application using a CAD/CAM system (SolidWorks).

Materials and Methods

The modeling and stress analysis of the spur gear is done using SolidWorks which is a commercially available CAD/CAM system. Furthermore, various constraints and boundary conditions imposed were taken into consideration. The Spur gear isometric view as shown in Figs. 1 and 2 were modeled using 3D SolidWorks.

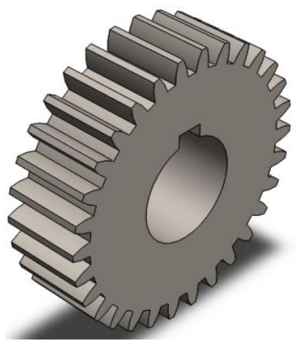

Fig. 1: Isometric view of a spur gear

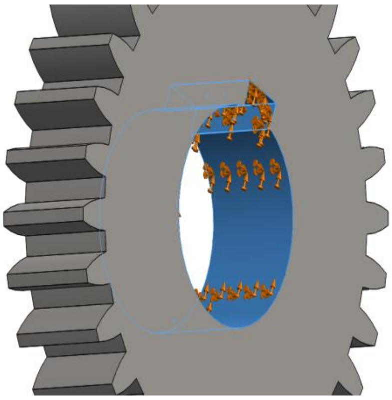

Fig. 2: Fixed region of the spur gear

The various constraints are:

1. Normal atmospheric pressure and temperature is assumed
2. The hole for shaft passage and key way is assumed fixed
3. The pitch circle diameter and number of gear tooth of the gears is fixed
4. Force of defined magnitudes is applied to two contact surface of spur gear

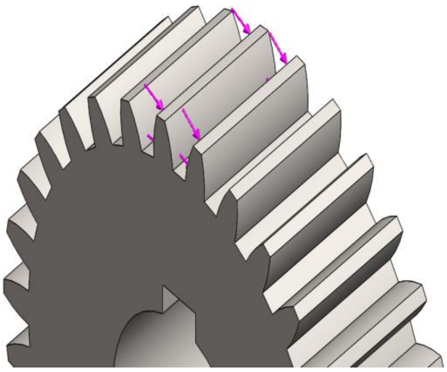

Fig. 3: Shows force applied normal at the contact surfaces of the spur gear

The spur gear is analyzed using plain carbon steel with teeth numbering 30, pressure and helix angle of 20º. The magnitude of applied forces is 400.34 N, 889.64 N and 1779.29 N to the spur gear contact surface.

SolidWorks FEA analysis

SolidWorks is a CAD/CAM system that permits the simulation of physical behavior of a part or assembly, to understand and improve mechanical performance of a design. It enables the analysis and optimization of designs for structural, thermal and dynamic requirements. The procedure involved in FEA analysis in SolidWorks is to primarily describe the geometry of the model, the physical features of the model and the mesh generation then the result is viewed and the explanation of the solution.

Steps involved in running analysis using SolidWorks

1. Model preparation: the spur gear model is prepared with SolidWorks
2. Material assignment: assign material for spur gear is plain carbon steel and cast
3. Element type definition: the definition of element type is by SolidWorks simulation having tetrahedral shape
4. Definition of element edge length: the element edge length is defined as 7 – 10 mm in order to generate a mesh.
5. Applied loads: the loads acting on the gear tooth were defined
6. Applied constraints/boundary conditions: the gear is fixed to the shaft such that it rotates with the rotation of the shaft
7. Analysis type definition: The type of analysis was defined as structural (static) analysis
8. Running the analysis: After the analysis is defined completed, it is required to run the analysis

Meshing criteria

Solid Works meshing functions was used to map the meshing. Higher-order(Second-order) parabolic solid tetrahedral element which has four corner nodes, six mid-side nodes, and six edges attached by meshing function for high quality mesh construction..

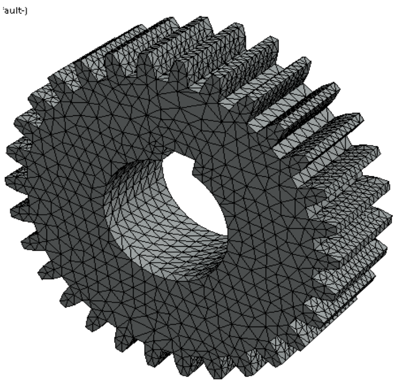

Fig. 4: Spur gear discretization

Results and Discussion

The design and analysis of plain carbon steel spur gear is conducted using SolidWorks CAD/CAM system. The analysis of the design is accomplished with the provided FEA application accessible by the system. The performance of the plain carbon steel spur gear is observed under the following force applications:

1. The application of 400.34 N force normal to the contact surface as illustrated in Fig. 5a presents a minimum and maximum stress development of 2.38712 x 10^{-5} Nmm^{-2} and 8.02425 x 10^{-1} Nmm^{-2} respectively in the gear. Fig. 5b indicates that the maximum displacement at the gear crown is 3.06303 x 10^{-4} mm. Fig.5c and 5d shows the deformation and factor of safety for a force of 400.34 N applied normal to the contact surface, respectively.

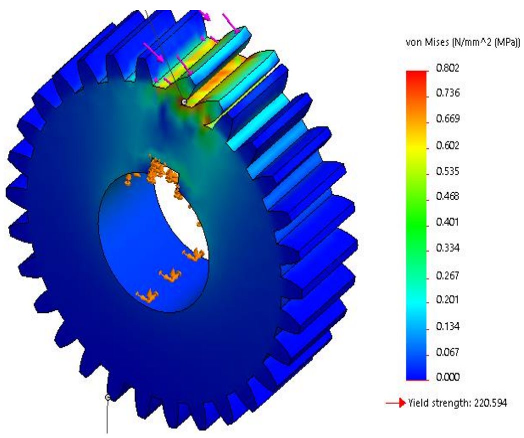

Fig. 5a: Stress distribution of plain carbon steel

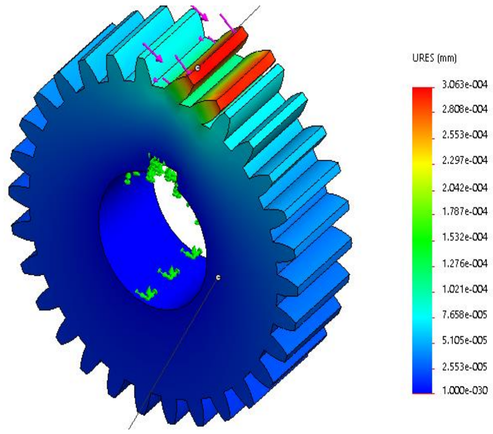

Fig. 5b: Displacement of plain carbon steel

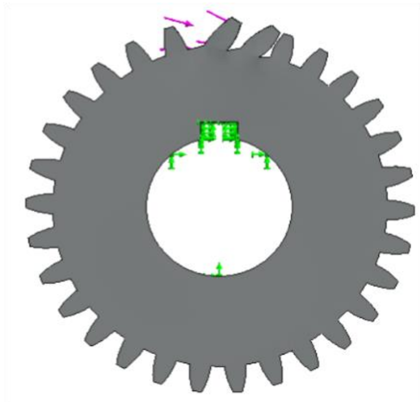

Fig. 5c: Deformation of plain carbon steel

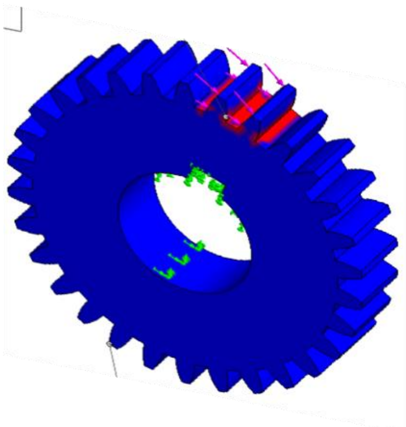

Fig. 5d: Factor of safety of plain carbon steel

2. The application of 889.64 N force normal to the contact surface as revealed in Fig. 6a presents a minimum and maximum stress development of 5.30472 x 10^{-5} Nmm^{-2} and 1.78317 Nmm^{-2} respectively in the gear. Fig. 6b indicates that the maximum displacement at the gear crown is 6.80674 x 10^{-4} mm. Fig. 6c and 6d shows the deformation and factor of safety for a force of 889.64 N applied normal to the contact surface respectively. Fig. 6d shows the ease by which the gear will fail when engaged as depicted by the red color observed at the root of the gear up to the pitch circle.

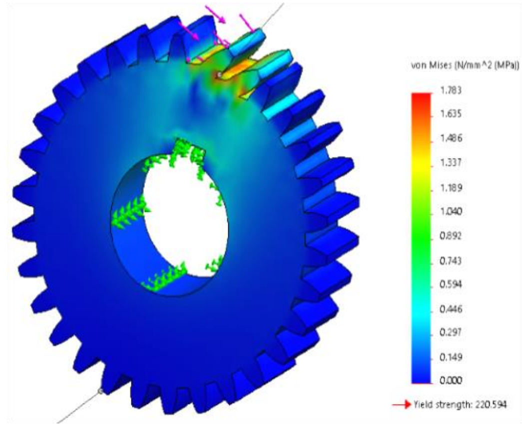

Fig. 6a: Stress distribution of plain carbon steel

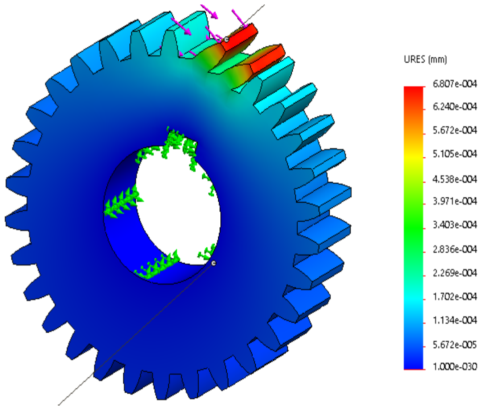

Fig. 6b: Displacement of plain carbon steel

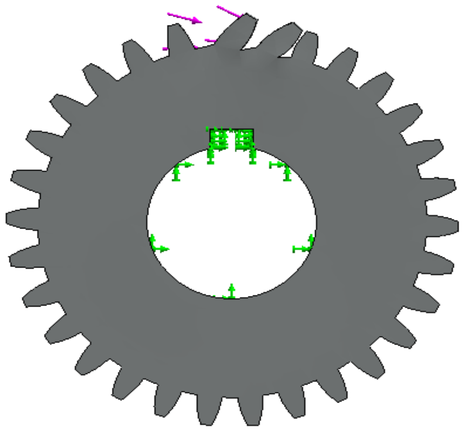

Fig. 6c: Deformation of plain carbon steel

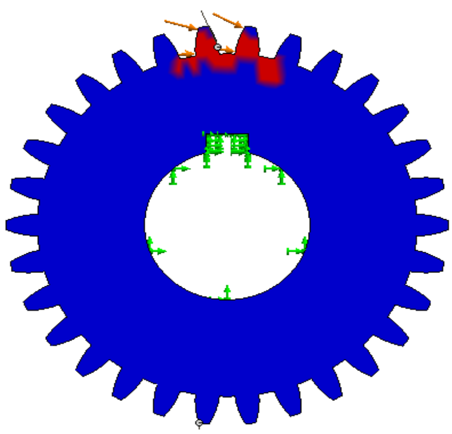

Fig. 6d: Factor of safety of plain carbon steel

3. The application of 1779.29 N force normal to the contact surface as indicated in Fig. 7a presents a minimum and maximum stress development of 1.06094 x 10^{-4} Nmm^{-2} and 3.56633 Nmm^{-2} respectively in the gear. Fig. 7b establishes that the maximum displacement at the gear crown is 1.36135 x 10^{-3} mm. Fig. 7c and 7d shows the deformation and factor of safety for a force of 1779.29 N applied normal to the contact surface respectively. Fig. 7c shows the area prone to deformation when the gear engages. Fig. 7d shows area of low factor of safety when engaged as depicted by the red color observed.

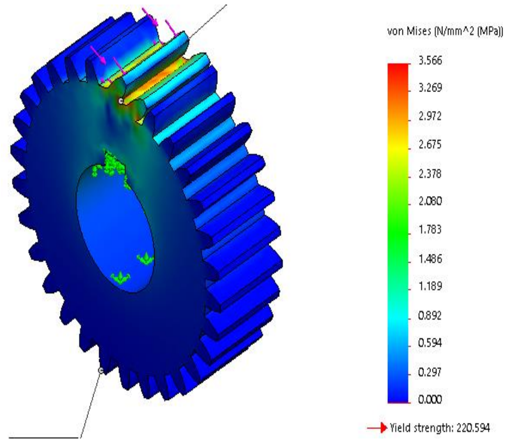

Fig. 7a: Stress distribution of plain carbon steel

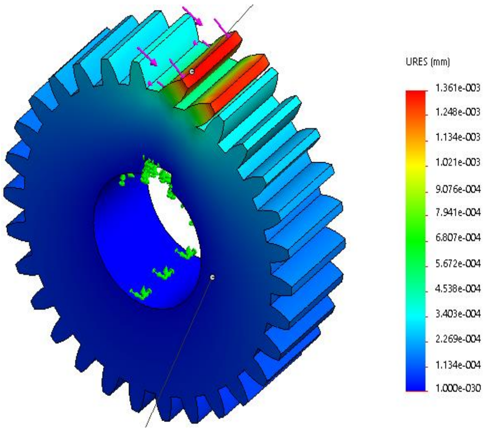

Fig. 7b: Displacement of plain carbon steel

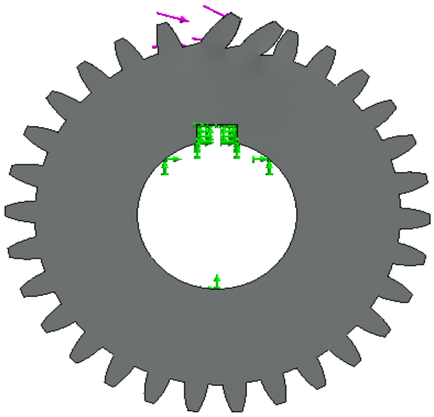

Fig. 7c: Deformation of plain carbon steel

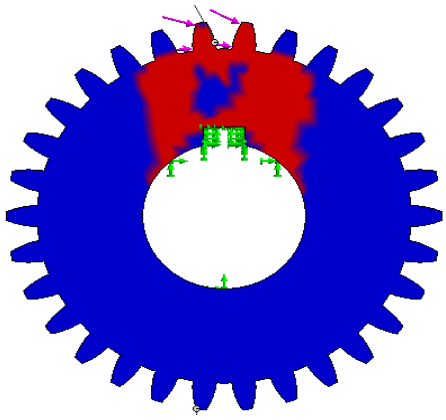

Fig. 7d: Factor of safety of plain carbon steel

The Table 1 presents the summary of the analysis. The analysis of the plain carbon steel material spur gear indicates that the maximum displacement occurs at the top face of the tooth for all the applied forces. It is noticed that the displacement observed in the gear is tremendously small and deflection occurs normal to the direction of applied force. For the materials used increase in applied force equally increases the displacement at the crown of the tooth and the induced stress accordingly. These findings is coherent with the findings of Mahendran *et al.* (2014) indicating that the induced stress in steel material increases with increase in applied force and torque.

Table 1 Result summary

Analysis Number	Applied force (N)	Von Mises Minimum stress (Nmm^{-2})	Von Mises Maximum stress (Nmm^{-2})	Maximum displacement at gear crown (mm)
1	400.34	2.38712 x 10^{-5}	8.02425 x 10^{-1}	3.06303 x 10^{-4}
2	889.64	5.30472 x 10^{-5}	1.78317	6.80674 x 10^{-4}
3	1779.29	1.06094 x 10^{-4}	3.56633	1.36135 x 10^{-3}

The maximum displacement for the gear occurs with the force application of 1779.29 N which is 1.36135 x 10^{-3} mm. The stress distribution is not uniform and the load intensity is at the big end. For these reasons, pitting, wearing and other tooth injuries will appear and the lifespan of gear will also be reduced.

Conclusion

The design and analysis using FEA offered by SolidWorks CAD/CAM system of a plain carbon steel spur gear under different force application has been presented with the vital details. The FEA is employed to analyze and determine the minimum and maximum stresses, maximum displacement at the gear crown, deformation and factor of safety of the spur gear for the applied forces. The analysis demonstrates the utility of FEA in simulating gear design and manufacture. The application of these procedures eliminates the need to rely upon unwieldy analytical representations of gear tooth geometry. (Analytical representations have heretofore been intractable except for the simplest of gear tooth surfaces).
Simulation results indicate that with the present design; stress, displacement at the gear crown and deformation increases

while factor of safety reduces. Therefore, the adoption of the FEA simulation method using a CAD/CAM system presented in this paper by decision makers will assist in making informed decision particularly about material selection and force application to which a spur gear is to be designed and subjected respectively to prevent failure. Similarly, improved design, elimination of design error and reduction in product lifecycle can be accomplished concurrently.

The method used is also a cost effective solution because single software is employed in the design and analysis. Finally, based on this result; if minimal induced stress at high force application is the prime concern of the design, then a spur gear with improved material characteristics such as composite material is recommended.

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