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Determination the Fatigue Life of Spur Gear through Stress Analysis with Optimization Methodology

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Abstract: Material selection is one of the most important decisions in optimal design of any manufacturing process and product. Proper material selection plays an elementary role for a productive manufacturing system with superior product and process excellence along with optimization. Improper material selection frequently causes enormous cost contribution and drives an organization towards immature product failure. A proficient methodology for material selection is thus required to help the manufacturing organizations for selecting the best material for a particular application. Developing an analytical approach and modeling procedure to evaluate stress distribution under velocity and moment would provide a useful tool to improve spur gear design with high efficiency. Based on the theories of gear engagement, contact analysis and friction, a three dimensional finite element model of the spur gear system was established to investigate stress distribution. A full-scale deformable-body model and a simplified discrete model were both shown to be accurate through extensive comparisons to the theoretical database generated in this study.
Keywords: Gear, MCDM, Stress Analysis, Fatigue, optimization

I. INTRODUCTION

A. Over view of Spur Gear

Spur gears are cylindrical shaped in which the teeth are parallel to the axis. It has the largest applications and, also, it is the easiest to manufacture. Spur gears are the most common type used. Tooth contact is primarily rolling, with sliding occurring during engagement and disengagement. Some noise is normal, but it may become objectionable at high speeds.

Smaller Gear is Pinion and larger one is the gear. In most application the pinion is the driver, this reduces speed but it increases torque.

1) *Tooth Stresses:* Stresses developed by Normal force in a photo-elastic model of gear tooth are shown in below (Fig. 1) .The highest stresses exist at regions where the lines are bunched closest together. The highest stress occurs at two locations:
   a) At contact point where the force F acts
   b) At the fillet region near the base of the tooth.

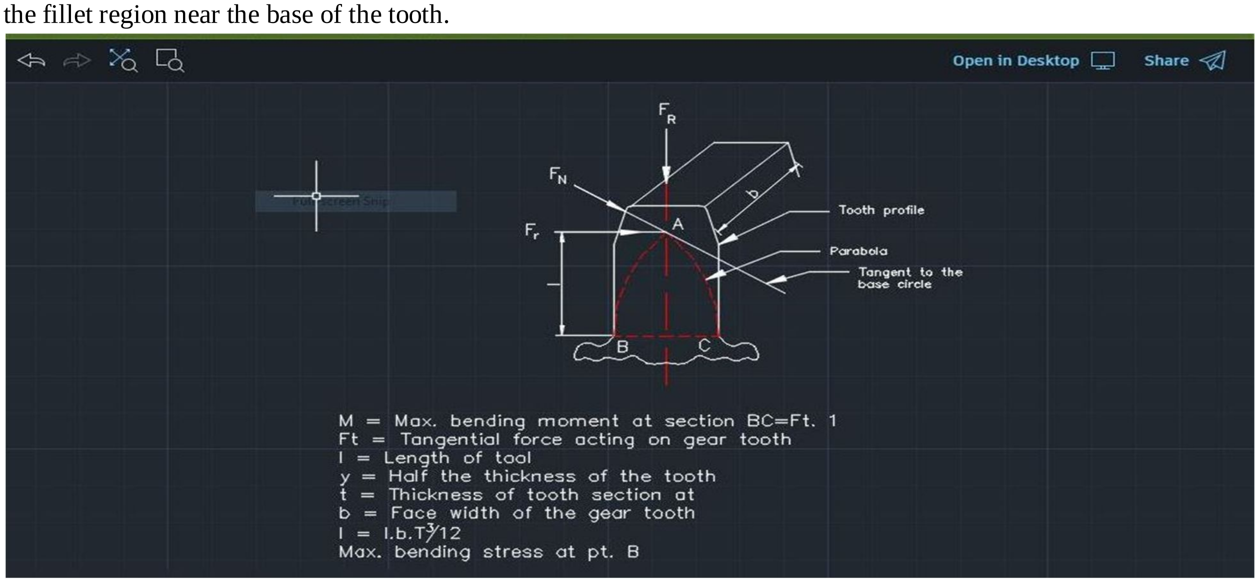

Fig. 1: Tooth Stresses

2) *Pressure Angle:* Pressure angle is the learning angle of gear tooth, an element determining the tooth profile (Fig. 2).

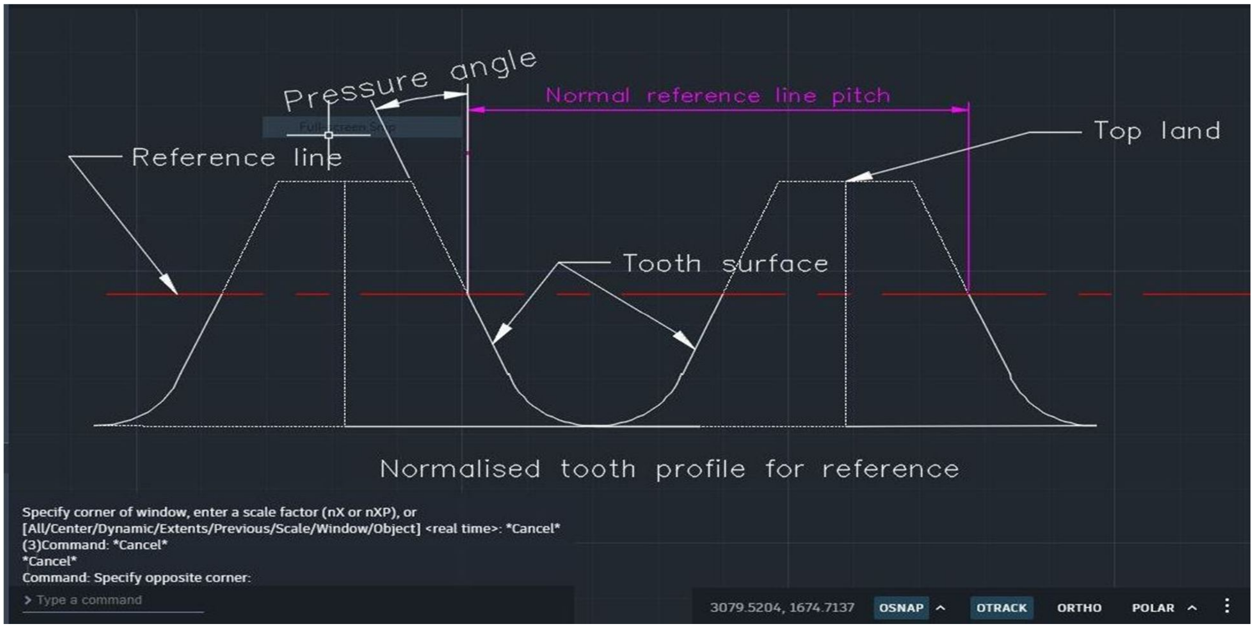

Fig. 2: tooth profile

B. *Gear Material Selection Models*

a simplified level, there are three factors that are most important when selecting a gear material. They are strength, durability, and cost, which include both the cost of the material and the cost of manufacturing. While the importance of these factors may vary from one project to another, the key to material selection is finding the right combination of physical properties that satisfy the requirements of the project at the lowest cost.. Mechanical properties of the material used to manufacture a product will define the behavior of the product under the action of any external force or stress during the mechanical operation. Some of the specific mechanical properties that should be considered in this project are as follow

1) Tensile strength
2) Density
3) Ductility
4) Wear resistance

Tensile strength of the material used will define the maximum force or the stresses that a product made of that particular make can take. So it is very important that the selected material should have good tensile strength. Density of the material will define the final weight of the product made by that material. So it is very important that the selected material should have low density so manufacture a light weight product. Ductility is the mechanical property which defines the mode deformation of ay product under stress. A ductile material first under goes, elastic deformation then plastic deformation and finally permanent failure whereas Brittle have no deformation modes and it fails after the yield point. So it is very important that the selected material should be ductile one. Wear resistance is one of the most important mechanical properties required for this project as meshing gears wear with time due to friction between the meshing teethes so material from which gears well me made should have excellent wear resistance.

C. *Material Performance Indices*

The main characteristics considered in the design of gears are:

1) Surface fatigue limit (Ssf),
2) Root bending fatigue limit (Sbf),
3) Wear resistance of tooth's flank
4) High tensile strength to prevent failure against static loads
5) High endurance strength to withstand dynamic loads
6) Low coefficient of friction
7) Good manufacturability

D. *Material Selection Process of spur Gear*

Optimal design of gears requires the consideration of the two type parameters: Material and geometrical parameters. The choice of stronger material parameters may allow the choice of finer geometrical parameters and vice versa. Very important difference among these two parameters is that the geometrical parameters are often varied independently. On the other hand, material parameters can be inherently correlated to each other and may not be varied independently. An example of which being the variation of the bending fatigue limit (Sbf) with the core hardness (HB) for some steel materials. If these parameters would be varied independently in an optimization case, it may result in infeasible solutions. Therefore, the final choice of material may not be possible within available data base. If gear material and geometrical parameters are optimized simultaneously then it is common to assume empirical formulas approximating a relation between material parameters for example the bending fatigue limit (Sbf) and ultimate tensile strength (UTS) as a function of hardness. If the choice of material is limited to a list of pre-defined candidates, then two difficulties can be appeared. First, a discrete optimization process should be followed against material parameters. Second, properties of different alternatives materials may not indicate any obvious correlation in the given list. The main goal is to choose material with best characteristic among alternatives.

E. *Material selection by MCDM*

1) *Multi Criteria Decision Making (MCDM):* Multiple criteria decision making (MCDM) is the process of selecting the best alternative from a set of feasible alternatives considering multiple conflicting criteria. In precise terms criteria are considered to be 'strictly' conflicting if the increase in satisfaction of one results in a decrease in satisfaction of the other. An MCDM process always contains at least two alternatives and two conflicting criteria (Bhattacharya et al., 2003). MCDM are divided two broad categories: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). Several useful tools for solving of MCDM problems are
   a) Simple Additive Weighting method (SAW)
   b) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
   c) Multi Objective Optimization Ratio Analysis(MOORA)
   d) Analytical Hierarchy Method (AHP)
   e) Analytical Network Method ANP etc.

F. *Simple Additive Weighting (SAW)*

1) *Step 1 Formation of Decision Matrix:* Criterion outcomes of decision alternatives can be collected in a table called Decision Matrix comprised of a set of columns and rows. The matrix rows represent decision alternatives, with matrix columns representing criteria. A value found at the intersection of row and column in the matrix represents a criterion outcome - a measured or predicted performance of a decision alternative on a criterion. The decision matrix is a central structure of the MCDA/MCDM since it contains the data for comparison of decision alternatives.

$$\begin{array}{cc} & \begin{array}{ccccc} C_1 & & C_j & & C_n \end{array} \\ X = \begin{array}{c} A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} & \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array}$$

xij is the performance rating of alternative i with respect to criterion j, Aj is ith alternative, Cj is the jth criterion

2) *Step 2 Formation of Weight Matrix:* Different importance weights to various criteria may be awarded by the decision makers. These importance weights forms the weight as follows.

$$W= [W_1 \ \cdots \ W_j \ \dots \ W_n] \quad (2)$$

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3) *Step 3 Normalization of Performance Rating:* Units and dimensions of performance ratings of columns under criteria differ. For the purpose of comparison, these performance ratings are converted into dimensionless units by normalization using following equations

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i (x_{ij})} \text{ for benefit criteria } \boldsymbol{j} \tag{3}$$

$$\bar{x}_{ij} = \frac{\min_i (x_{ij})}{x_{ij}} \text{ for non-benefit criteria } \boldsymbol{j} \tag{4}$$

Normalized decision matrix

$$\bar{X} = \begin{array}{c} A_1 \\ \vdots \\ A_2 \\ \vdots \\ A_m \end{array} \begin{bmatrix} \bar{x}_{11} \cdots & \cdots \bar{x}_{1j} \cdots & \bar{x}_{1n} \\ \vdots & \vdots & \vdots \\ \bar{x}_{i1} \cdots & \cdots \bar{x}_{ij} \cdots & \bar{x}_{in} \\ \vdots & \vdots & \vdots \\ \bar{x}_{m1} & \bar{x}_{mj} & \bar{x}_{mn} \end{bmatrix}_{m \times n} \tag{5}$$

4) *Step 4 Composite Score:* Computation of composite score (CS_i) for alternative *i*

$$CS_i = \sum_{j=1}^{n} (\bar{w}_j * \bar{x}_{ij})$$

5) *Step 5 Ranking and Selection of best Alternative:* Ranking of products in descending order of composite scores (CS_i).

G. *Entropy*

Entropy was originally a thermodynamic concept, first introduced into information theory by Shannon (see Shannon, 1948 [21]). It has been widely used in the engineering, socioeconomic and other fields. According to the basic principles of information theory, information is a measure of system's ordered degree, and the entropy is a measure of system's disorder degree.

1) *Step1* Calculate p_{ij} (the ith scheme's jth indicator value's proportion).

$p_{ij} = r_{ij} / \sum_{j=1}^{m} r_{ij}$, r_{ij} is the ith scheme's jth indicator value.

2) *Step2* Calculate the jth indicator's entropy value

e_j. $e_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}$, $k = 1/\ln m$, m is the number of assessment schemes.

3) *Step3* Calculate weight wj (jth indicator's weight).

$$w_j = (1-e_j)/\sum_{j=1}^{n}(1-e_j), \; n \text{ is the number of indicators,}$$

$$\text{and } 0 \le w_j \le 1, \sum_{j=1}^{n} w_j = 1.$$

In entropy method, the smaller the indicator's entropy value ej is, the bigger the variation extent of assessment value of indicators is, the more the amount of information provided, the greater the role of the indicator in the comprehensive evaluation, the higher its weight should be.

H. Stress Analysis of a spur Gear

1) *Spur Gear Contact:* The transfer of power between gears takes place at the contact between the acting teeth. The stresses at the contact point are computed by means of the theory of Hertz. The theory provides mathematical expressions of stresses and deformations of curved bodies in contact. Fig. 1 shows a model applied to the gear-two parallel cylinders in contact.
2) *Contact Periods:* It is clear that during the rotation operation of the mating gears each tooth will share load in double tooth contact stage and will carry the entire load at single tooth contact, and the contact ratio is the most important parameter which plays in this situation. The contact path length, the contact ratio and the angle which is corresponding to this contact length which is the most important feature here in this section compared to the other following sections, because the contact stages will be investigated and analyzed by dividing this angle into any desirable angular periods or angular intervals.\

3) *Three Stages of Tooth Contact*

The teeth of two gears during operation (or mesh) pass through three stages of contact:

a) Coming into mesh, initial contact occurs in the dedendum (lower) portion of one tooth (on the driving gear) and in the addendum (upper) portion of the mating tooth (on the driven gear). At this point of torque transfer, tooth loading (LT) is relatively light, since most of it is carried by the teeth in full mesh and a portion by the teeth going out of mesh. Contact between the two teeth moves in a sliding action as they proceed through mesh. The sliding velocity (VS) decreases until it is zero when the contact points reach the intersection of their common pitch lines.
b) At full mesh, the two teeth meet at their common or “operating” pitch line, there is only a rolling motion, no sliding. However, this stage produces the greatest tooth loading.

Coming out of mesh, the two mating teeth also move in a sliding action, basically opposite of the initial contact stage.

4) *Spur Gear - Tooth Bending Stress*

Factors that influence gear tooth bending stresses are as follows:

a) Pitch line velocity.
b) Manufacturing accuracy.
c) Contact ratio.
d) Stress concentration.
e) Degree of shock loading.
f) Accuracy and rigidity of mounting.
g) Moment of inertia of the gears and attached rotating Members.

I. Fatigue of a Spur Gear

1) *Fatigue:* Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. If the maximum stress in the specimen does not exceed the elastic limit of the material, the specimen returns to its initial condition when the load is removed. A given loading may be repeated many times, provided that the stresses remain in the elastic range. Such a conclusion is correct for loadings repeated even a few hundred times. However, it is not correct when loadings are repeated thousands or millions of times. In such cases, rupture will occur at a stress much lower than static breaking strength. This phenomenon is known as fatigue.
2) *Factors that Affect Fatigue-life*

a) *Cyclic Stress State:* Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or out-of-phase shear stress, and load sequence,
b) *Geometry:* Notches and variation in cross section throughout a part lead to stress concentrations where fatigue cracks initiate.
c) *Surface Quality:* Surface roughness cause microscopic stress concentrations that lower the fatigue strength. Compressive residual stresses can be introduced in the surface by e.g. shot peening to increase fatigue life. Such techniques for producing surface stress are often referred to as peening, whatever the mechanism used to produce the stress. Low plasticity burnishing, laser peening, and ultrasonic impact treatment can also produce this surface compressive stress and can increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue.

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d) *Material Type:* Fatigue life, as well as the behavior during cyclic loading, varies widely for different materials, e.g. composites and polymers differ markedly from metals.
e) *Residual Stresses:* Welding, cutting, casting, and other manufacturing processes involving heat or deformation can produce high levels of tensile residual stress, which decreases the fatigue strength.
f) *Size and Distribution of Internal Defects:* Casting defects such as gas porosity, non-metallic inclusions and shrinkage voids can significantly reduce fatigue strength.
g) *Direction of Loading:* For non-isotropic materials, fatigue strength depends on the direction of the principal stress.
h) *Grain Size:* For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse grained alloy.
i) *Environment:* Environmental conditions can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Corrosion fatigue is a problem encountered in many aggressive environments.
j) *Temperature:* Extreme high or low temperatures can decrease fatigue strength.
k) *Crack Closure:* Crack closure is a phenomenon in fatigue loading, during which the crack will tend to remain in a closed position even though some external tensile force is acting on the material. During this process the crack will open only at stress above a particular crack opening stress. This is due to several factors such as plastic deformation or phase transformation during crack propagation, corrosion of crack surfaces, presence of fluids in crack, or roughness at cracked surfaces etc. this will provide a longer fatigue life for the material than expected, by slowing the crack growth rate

J. Fatigue calculation of a spur Gear

1) *Basquin's equation: stress amplitude* $=\sigma_f{}'(2N)^B$

2N= number of load reversals to failure (N = number of cycles to failure)

σ_f' = fatigue strength coefficient defined by the stress

B= fatigue strength exponent, which varies between –0.05 and -0.12 for most metals

2) *Research Agenda:* The materials and process selection are key issues in optimal design of industrial products like gear. The materials and process selection are key issues in optimal design of industrial gears. Substituting and selecting materials for different machining parts is relatively common and often. Material selection is a difficult and subtle task, due to the immense number of different available materials. One the most suitable models, for ranking alternatives gear materials, is SAW which using a multiple criteria, which all material performance indices and their uncertainties are accounted for simultaneously. After finding proper material, fatigue life is more important as any product. Through stress analysis it is easy to calculate to find out the product life cycle by autodesk inventor. This paper concerns about increment the decision of material selection of gear manufacturing process and improvement the machinability, accuracy, quality with the industrial view. Overall improvement of optimal design of a gear in manufacturing process considering the fatigue life and other aspect of materials.

II. WORK & RESULT

A. Material Selection using MCDM by MATLAB

1) *Experiment:1:* Suggested materials and their properties in a gear material selection problem

Material	Surface (Bhn) Hardness	Core (Bhn) Hardness	Surface fatigue limit (MPa)	Bending fatigue limit (MPa)	UTS (MPa)
Cast iron	200	200	330	100	380
Ductile iron	220	220	460	360	880
Carburised steel	650	300	1500	920	2300
Nitrided steel	700	300	1250	760	1250
Through hardened carbon steel	200	190	500	430	620
Weighted of material	W_1	W_2	W_3	W_4	W_5

Data are taken form Hofmann (1990) where Vickers hardness values have been converted to Brinell values using conversion tables in http://www.gordonengland.co.uk/hardness/brinell_conversion_chart.htm

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a) Entropy Method Result

The waighted values are:

W_1= 0.1868, W2=0.1273, W_3 = 0.2001, W_4= 0.2408, W_5= 0.2450

Here,Benificial column=5

& Non Benificial column=0

b) Saw Result

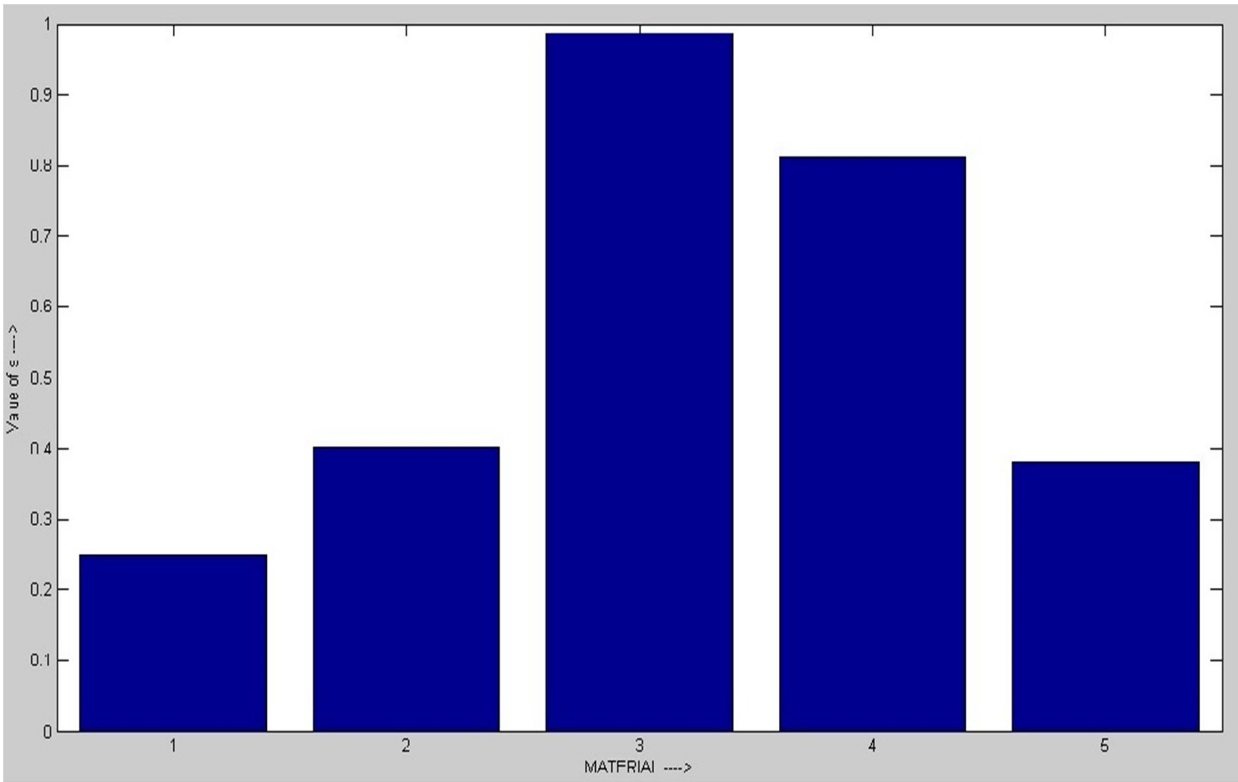

Fig. 3: Ranking Graph

Above (Fig. 3) the suggested materials and their properties in a gear material selection problem, the best material is Carburized steel.

2) *Experiment: 2:* This experiment ventures one of the major concerns in the field of various machine, which is to predict the service life of spur gear, used in automobile. This experiment addresses the phenomenon of characterizing the stress analysis of the ground spur gear and to calculate the service life of spur gear where each of them has different pressure angle and hence, the cam with maximum fatigue life is selected.

a) Data

- Pitch dia of pinion=96=D_P
- Face width=84=b
- Ratio factor=1.5=Q
- Load stress factor=k=$\frac{(6es)sin\emptyset}{1.4}[\frac{1}{Ep}].[\frac{1}{Eg}]$

Here, 6es=surface endurance limit=600mpa

Ø=pressure angle=18^0

E_p=young's modulus for the material of pinion=200mpa

E_g= young's modulus for the material of gear=100mpa

Wear tooth load=W_W= $D_{P.}$ b. Q. k=14394.24 N

Showing the stresses from stress analysis by Autodesk Inventor (Fig.-4 & 5)

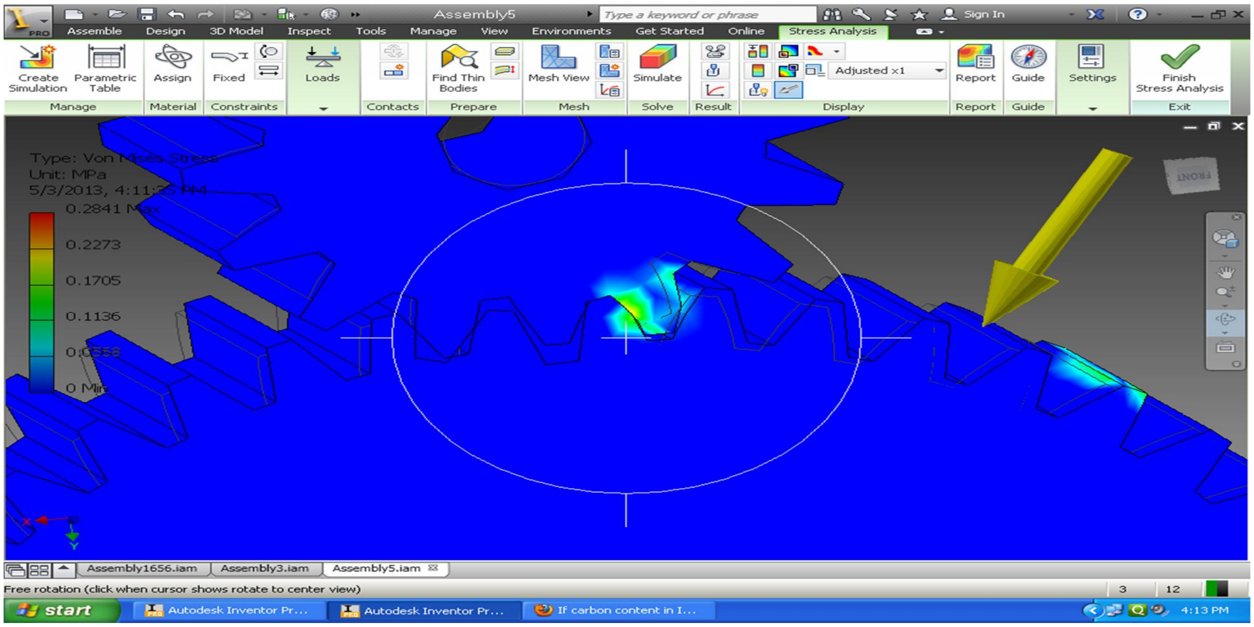

Fig.-4

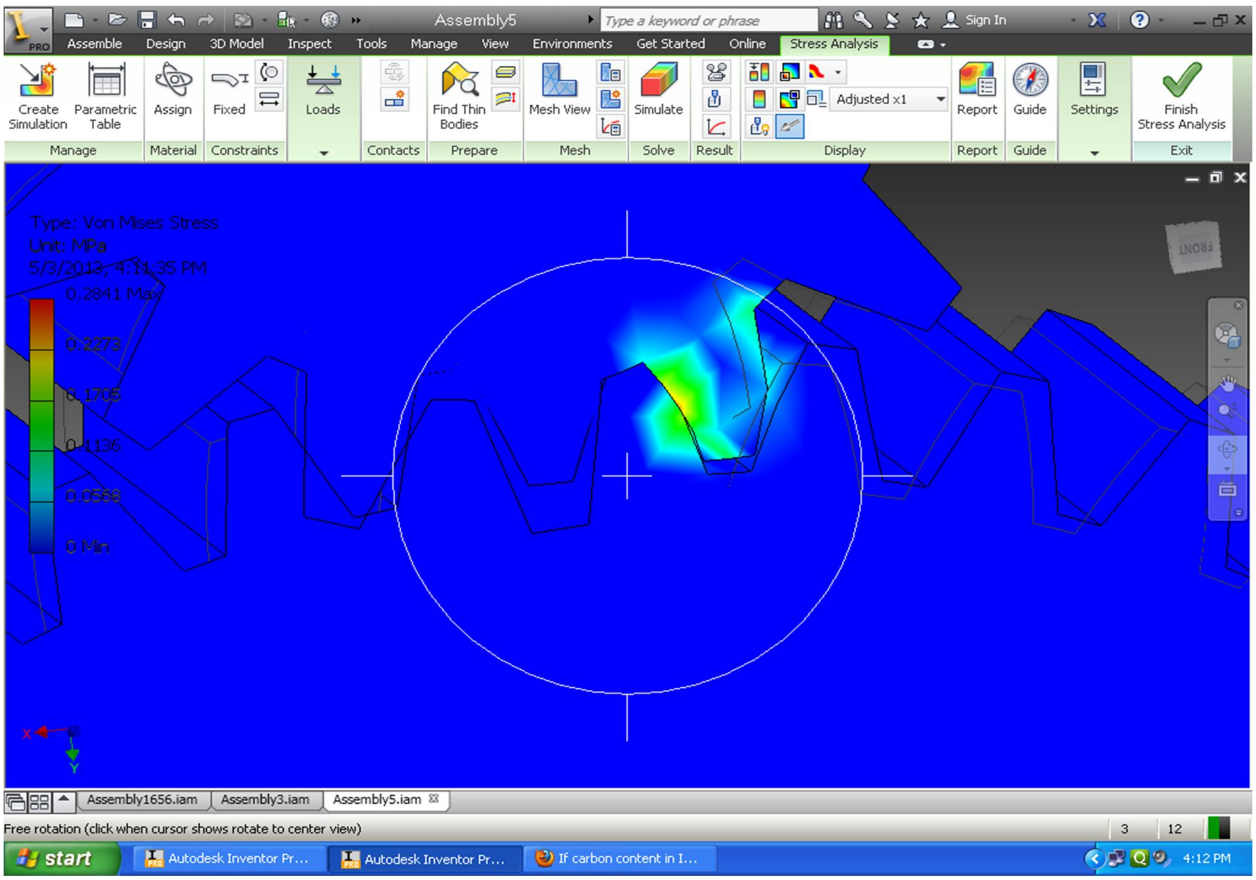

Fig.-5

$\emptyset=18^0$
$\sigma_{max}=0.2841$

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This stresses are repeated stress(Fig.-6), so the σ_{min}=0

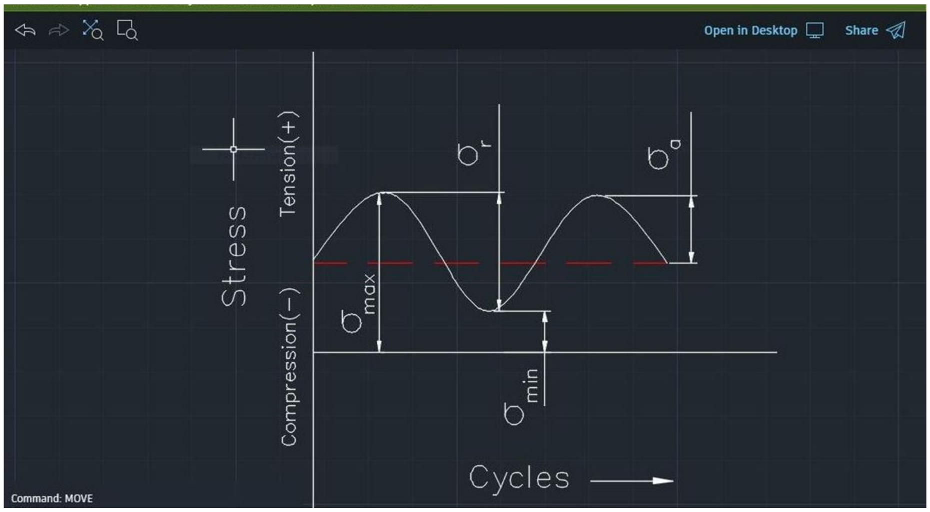

Fig.-6 repeated stress

- $\sigma_{mean}=\frac{6max+6min}{2}$
- stress amplitude, $\sigma_a=\frac{6max-6min}{2}$

Table1

Pressure angle	σ_{max}	σ_{min}	σ_{mean}	stress amplitude
18^0	0.2841	0	0.142	0.142

B. Fatigue Life Calculations from Stress Analysis

The various modes of contact-fatigue failure between a gear and a pinion can be classified according to their appearance and the factor which promote their initiation and propagation.

The main failure modes of the gear-pinion configuration are scuffing and pitting. The probability of one of these occurring depends on several parameters such as material properties, lubricants, loads, engine speed, and temperature.

Here due to change in pressure angles the contact stress also varies so For the high-cycle (low strain) fatigue (HCF) regime, where the nominal strains are elastic, Basquin's equation can be reformulated to give:

Stress amplitude = $\sigma_f'(2N)^B$

WHERE,

2N= number of load reversals to failure (N = number of cycles to failure)

σ_f' = fatigue strength coefficient defined by the stress = 490

B= fatigue strength exponent, which varies between –0.05 and -0.12 for most metals = -0.071

C. Calculating the Fatigue life by this Equation

Number of life cycles = 3.398×10^{49}

III. PLAN OF FUTURE WORK

The proposed research work is planned into different stages: Objective setup, analysis of parameter and design of experiments, experimentation and validation of results, alternative solution search. In first phase different specification of material will be chosen form literature review & experiment for analysis and improvement, such as exploring the best selection of gear material by MCDM, minimization of material selection risk and analysis the fatigue life the best chosen material.

In second phase The project research can be taken to the next level by designing in CATIA and finding the stress analysis by ANSYS and implementation of Finite Element Analysis (FEA) and henceforth comparing the life cycles. Application of software like Delcam would convert this theoretical approach to the final product, which in turn, would be of great help in automobile industries and the ultimate aim will be fulfilled.

IV. CONCLUSION

In this study, theoretical investigations on the gear characteristic were conducted to quantify their influence on gear stress and deflections. The deformable-body model of the spur gear system with the same condition was developed proper selection methodology. The deformable-body model matches very well with the measured result from theoretical calculation and discrete-body model. The spur gear system in the present thesis carries on the basic analysis and compare with exsiccation gear. A 3D deformable-body model of spur gears was developed. The result is checked with theoretical calculation data. The simulation results have good agreement with the theoretical results, which implies that the deformable-body model is correct. This study provides a sound foundation for future studies on the other gear series: Helical gear, annular gear, turbine wheel and so on. The model was applied onto Autodesk Inventor 2013. Simulation results were compared and confirmed by the theoretical calculation data.

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