Comparative Finite Element Analysis of Reconstructed New and Worn Tooth of Spur Gear

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***Abstract*— Spur gear wears either due to rubbing action between the meshed gears or by the occurrence of unwanted elements like dust particles, metal fragments, etc. which reduces its efficiency and service life. It is always a challenging task to determine the remaining life of a component or the strength of a component once wear has occurred on teeth surface. This paper presents an application of reverse engineering approach for reconstruct the spur gear 3D CAD model using scanned data. A gear has been scanned using PICZA 3D laser scanner (Roland LPX60). The digitized data of spur gear was collect in the form of .stl data and point cloud data file formats. The scanned spur gear has been reconstructed in 3D CAD model before and after wear using SolidWorks modeling software. The finite element analysis has been carried out for tooth strength assessment between original and worn out gear teeth. These results were obtained on ANSYS Workbench. The results will allow for a better understanding of existing limitations for power transmitting with worn out gear tooth and also may be helpful to determine remaining life cycle of gear under loading conditions.**

Keywords- spur gear; reverse engineering; 3D laser scanner; reconstruct of 3D CAD model; FEM analysis

I. INTRODUCTION

The reverse engineering under the mechanical engineering environment is extremely important methodology for geometric design and manufacture applications. Revere engineering is usually undertaken in order to re-design or to re-producing design details in the form of CAD model for better maintainability, reparability, interchangeability and overhauling of exiting physical models. To re-contrast the traditional production sequence, reverse engineering typically starts with measuring an existing object, so that CAD model of existing object can be deduced in order to make use of the advantages of CAD/CAM/CAE technologies. The reconstructed CAD models can be used for error analysis, FEM analysis, and rapid prototyping and in manufacturing process. In present, the reverse engineering approach is conventional processes for product design and development and manufacturing process. This technique has been extensively recognized as being a major step to significantly reduce the product development cycle time. The reverse engineering process is necessary in design phase because of following aspects [1, 2]:

- Some physical objects are available but there design or manufacturing documentations are not available.
- For rapid tooling and recovery of broken moulds or duplicating mould in the injection moulding industry.
- The reconstructed CAD model may be precise compared with the true surface of the part if the part surfaces are damaged or worn out.
- The engineer may have completed the product function and aesthetics design based on the requirements and these products are fabricated on some soft materials, such as wood or plaster etc.
- Designer can compare the model, using reverse engineering with any scanning techniques after reconstructing the 3D-CAD models.

Reverse engineering has advantage over the conventional engineering process in terms speed to re-construct CAD models. The existing physical model is used as the preliminary step so, it can be help to reduction in development process time and production cost. The uses of 3D-digitising technique for complex surface machine elements have some advance innovation technology in computational manufacturing. Manufacturing industries are prompt with the applications of reverse engineering for detection of the operation error in machine elements, quality control, inspection, direct replication of parts, redesign of parts, and manufacturing tools. The process consists of digitization of physical models. Digitization of object surface using reverse engineering can be achieved by either noncontact or contact scanning methods. Noncontact scanning devices are faster and more accurate compared to contact probing devices. The digitized surface of an existing model can be transform into point cloud or .stl data file formats using inbuilt scanning software. Such scanned data allow to re-creating 3D-CAD models, using any suitable modeling software to perform the engineering operations and finite element analysis (FEA).

Gear is a machine element concerned with transmission of power and motion between rotating shafts. Gear has effective transmission torque and stationary transmission ratio with high transmission efficiency and long service life. Because of complicated structure and adverse working conditions gear may be caused, its tooth wear. In practically, different types of wear on gears tooth may be developed due to variety of materials, heat treatments and working conditions. It has been seen that the glue take palace due to fatigue, crack and plastic deformation by rubbing action between the meshed gears or by dust particle, metal debris, etc. Worn out spur gear teeth cause the some problems like increased the acoustic noise during operation, increase the backlash, change in center distance and losses of transmitted power, these effecting parameters are effect on gear efficiency and service life. For closer control over the remaining life cycle of the gear, precision measurement and analysis of gear tooth play a vital role. Spur gear have the majority among all types of gear in use therefore analysis of spur gear tooth using reverse engineering becomes a persisting target. It is use full to do some researches on worn out gear tooth using revere engineering approach.

Reverse engineering has been used for scan the spur gear with wear and without wear and study the effect of stresses on worn out gear tooth using ANSYS workbench. The reconstructed spur gear CAD models have been used to verify the stress/strain limits under the mechanical behavior. Using this approach we can identify the critical zones vulnerable for stresses and also estimate the remaining life of a component.

II. Steps Involved in The Reverse Engineering

Reverse engineering deals with the detailed study of the product including its material, structure, surface qualities, operating conditions etc. The first step involved is the collection of data followed by preprocessing and solid model creation.

Reverse engineering is the process of scanning an object and then generating a CAD model. The methodology used in the current work is explained by flow chart shown in Figure 1. The following steps are used for the proposed methodology:

- Step 1: Scanning of spur gear before wear and after wear.
- Step 2: 3D data collection in point cloud data /.stl data format.
- Step 3: Generate the curve/surface using scanned data.
- Step 4: Analyze the scanned data for every tooth with respect to z.
- Step 5: Reconstruct the 3D CAD model of spur gear using modeling software.
- Step 6: Generated 3D CAD model can be import into ANSYS workbench with IGES format.
- Step 7: Complete the FEM analysis with suitable boundary conditions.
- Step 8: Compared the result of original gear and worn-out gear tooth.

III. Design Details of Spur Gear

The spur gear has been designed according to AGMA standard for present study and using gear design handbook [3].

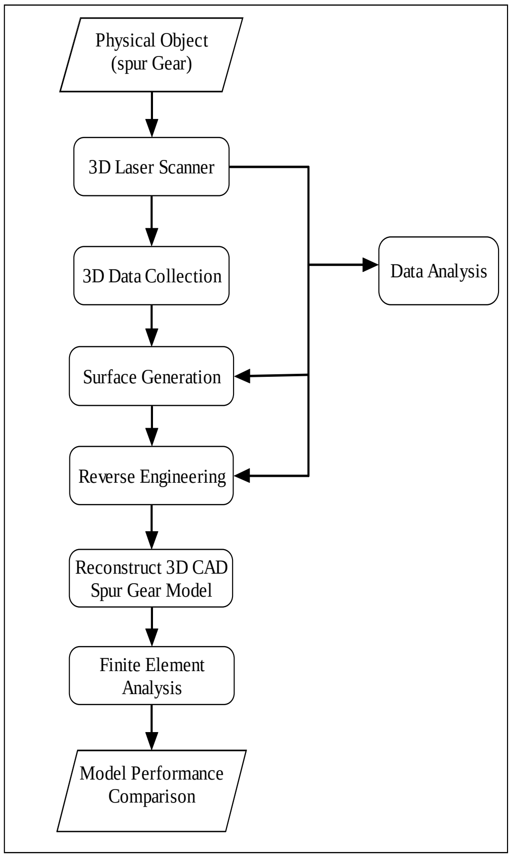


Fig. 1. Overall procedure for the proposed methodology.

The specifications used to design the spur gear are presented in table 1.

TABLE I. DIMENSION AND PARAMETERS FOR STANDARD 20^0, FULL DEPTH INVOLUTE SPUR GEAR

Parameters	Relation With Module (= 6.35) mm	Calculated Value (mm)
Addendum (a)	m	6.35
Dedendum (d)	1.25m	7.94
Tooth thickness	1.5708m	10
Tooth space	1.5708m	10
Working depth	2m	12.7
Whole depth	2.25m	14.3
Pitch diameter	Zm	76.2
Outside circle diameter	(z+2)m	89
Root circle diameter	(z-2.5)m	60.325
Fillet radius	0.4m	2.54
Material	AISI1040 (40Mn2)	
Tensile strength	620MPa	
Yield strength	415MPa	
Modules of elasticity	200GPa	
Density	7845 kg/m^3	
Poisson’s ratio	0.3	
Number of tooth	12	

The photographic view of the spur gear both before and after wear has been shown in figure 2(a) and (b) respectively.

(a)

(b)

Fig. 2. Images of spur gears (a) Before wear (b) After wear

IV. 3D Laser Scanning and Digitization of Spur Gear

3D-Laser scanner devices scan the surface profile of a physical model by a striped laser beam and CCD cameras captures profile images and generates digital data. The laser stripe by triangulation method measures hundreds of surface points per second. This 3D-laser scanning system (PICZA 3D laser scanner Roland LPX60) stripes coordinate point data. Limitation concerning scan surface preparation for laser scanning requires spraying of matt white paint on the surface to be scanned and owing to this scanning point accuracy is close to actual surface geometry. To achieve same features of the part, in each scan a reference point was marks on scanning object and on a rotary table. Gear has been scanned for five different face angles such as 10, 40, 70, 80 and 90 degrees and the least noise was found with 80-degree face angle as shown in figure 3.

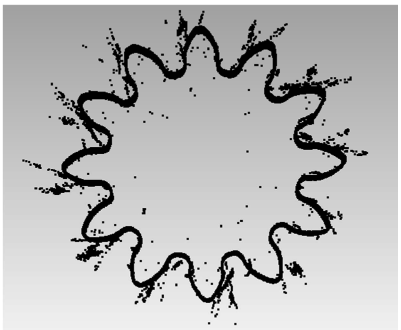


Fig. 3. Point cloud data of spur gear.

The scanned data usually contain some noise in the form of spikes, outlier and some poor quality regions because of this scanned data cannot be directly used for surface modeling operation. Some preprocessing processes are required for remove overlapped point data and data filtering to be carried out to reduce the noise of the scanned data [4]. The spur gear has been digitized using scanning tool (Roland LPXEZ studio) and scanned data has been saved in .GSF file format. Noise free data of spur gear is required for part modeling or recreation at every fixed height of teeth profile along with Z axis. This scanned data will result in a series of stair-steps of profile curves and features can be co-related along the Z - axis for CAD model making. The digitized data after 3D scanning of the spur gear is in point clouds /.stl file format. It is used as output of scanned data. The numbers of scanned data in X, Y and Z coordinates for original gear are 453645 and for worn out gear are 452742.

V. Processing and Segmentation

The scanned data from different scan directions should be combined in one coordinate system, which is called registration [5]. In fact, data acquired by laser scanner devices always contains some noise. It can be introduced in multiple ways, from extraneous vibrations, specular reflection, unexpected light disturbances, sharp edge, invisible occluded surfaces region etc. For the processing process the steps involved are, count, noise filtering, data smoothening and data reduction. In this work, the 3D editor (version 2.0) tool of Dr. PICZA3 has been used for editing and removing the noise from scanned surface models. The processed image of spur gear is presented in Figure 4.

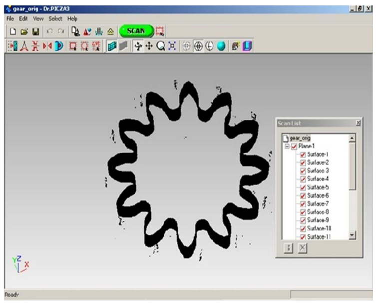


Fig. 4. Preprocessed surface profile of spur gear.

The aim of segmentation is to produce a representation of the shape of the object and generate a set of surfaces from subdivided point cloud data. Segmentation of the surface model is carried out in order to logically divide the original point set into subsets, such that each subset point contains sampled for a particular scanned surface shown in figure 5.

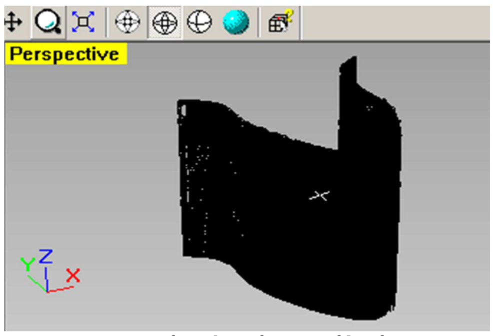


Fig. 5. Isometric views of tooth surfaces profile after segmentation.

VI. RECONSTRUCTION OF SPUR GEAR 3D CAD MODEL

The CAD model is re-creating after the processing of scanned data using SolidWorks modeling software. The input data in SolidWorks must be in .txt or .ibl formats. The processed data can be used directly for the creation of curves to surfaces and then CAD model.

A. Curve Construction

The output data of scanned gear shows X, Y and Z coordinates location. The format of the scanned data (.stl and point cloud data) which is used as output data must be transformed into acceptable file formats for it being used in SolidWorks modeling software or other capable software's. Pre-proceed data has been saved as a .txt format for all teeth at different values of Z i.e. 0, 1, 2, 3….. (up to14mm). The saved data aging convert in the .ibl format which is acceptable format by SolidWorks modeling software. The changed data format has been import in SolidWorks and sketched the curves profiles for the different values of Z (i.e 0, 2, 4...14) as showing in figure 6. Every curve has been generated by joining the point to point and has some curvature difference between original and worn out tooth profile. As a result, the generated teeth curves/surfaces will have better smoothness.

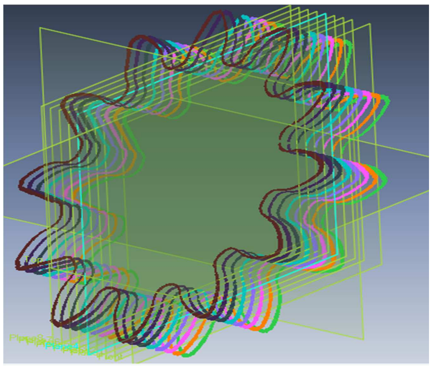


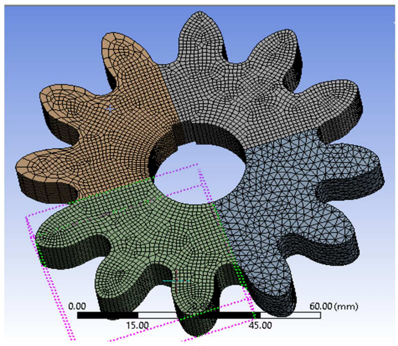
Fig. 6. Sketch teeth profile curve for different values of Z.

B. CAD Model Construction

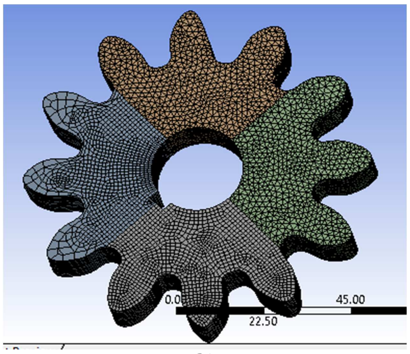
3D CAD model can be recreated in two ways using measurement data in free-form feature modeling tool: first is curve mode and second is surface mode. The curves construction is generated from measurement data first, and then the surface can be created through the construction curve. But in surface mode, the surface is generated directly from measurement data. The offset distance of measurement data is in the form of coordinate's values for scanned objects [6]. In present work, uses the first approach, here the curves has been sketched by joining the scanned points then spur gear CAD model has been created by lofting the sketched curves on SolidWorks.

VII. STATIC FORCE ANALYSIS

In present study, the gear teeth has been taken with regardless to find out the statics force analysis through performance parameters like tooth bending, tooth contact stress for original gear and worn out gear. These parameters may be basic modes of fatigue failure of any toothed gearing. The gear design specifications calculated using AGMA standard has been shown in table I. This model design is based on AGMA design parameters and imported on ANSYS Workbench 14.0. The reconstructed 3D CAD models of original gear and worn-out gear with meshing have been shown in figure 7 (a) and (b) respectively.



(a)



(b)

Fig. 7. Spur gear CAD model (a) Original spur gear meshing (b) Wear out spur gear meshing.

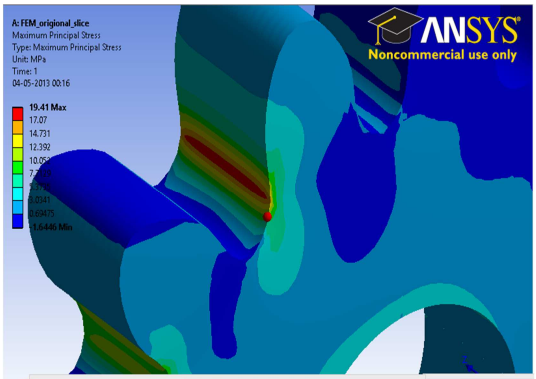
Finite element analysis for the rebuilt spur gear CAD model is carried out by using non commercial software of ANSYS Workbench, which can directly import from SolidWork, thus greatly reduce geometric error. The chosen material is alloying steel AISI-4010. The rebuilt CAD model is divided in irregular mesh, and the total number of elements is 2132. Finite element method is use for analyzing the stress of original and worn-out recreated spur gear tooth. The above parameters have been calculated under load conditions at the line of contact location. The loads have been calculated based on AGMA standard. The calculated values of radial force is 455 N (in X direction) and the tangential force is 1250 N (in Y direction) for transmission of 7 kW power at 1400 rpm. The various values of forces obtained both in X and Y direction under different percentage of the pre define load has been shown in table II.

Finite element analysis for the rebuilt spur gear tooth can be regarded as a static problem, thus only the maximum stress including the maximum compressive stress needs to be analyzed. In view of working condition for original and worn out spur gear tooth may be supposed to be same.

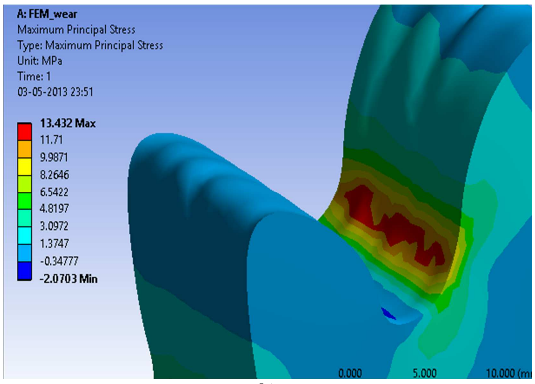
Loading and parameters effect has been performed for worn out gear tooth. Finite element results have been obtained and shown in figure 8 (a) and (b) for original tooth and worn-out tooth respectively. In the static Finite element analysis, whether the part meets the requirements or not is mostly evaluated by total deflection, equivalent stress, maximum shear and maximum principal stress.

TABLE II. ACTING LOAD ON TOOTH

S. No.	Load		
	% of Define Load	*Load Values in X Direction (N)*	*Load Values in Y Direction (N)*
1	1	455	1250
2	25	569	1563
3	50	683	1875
4	75	797	2188
5	100	910	2500
6	125	1024	2813
7	150	1138	3125
8	175	1252	3438
9	200	1365	3750



(a)



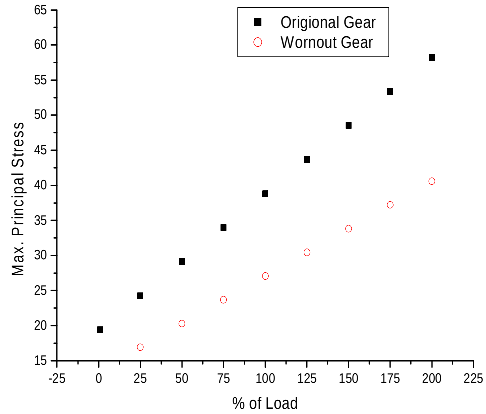
(b)

Fig. 8. Effective stress distribution on loaded gear tooth (a) Along Z- axis for original gear (b) Along Z -axis for worn-out gear.

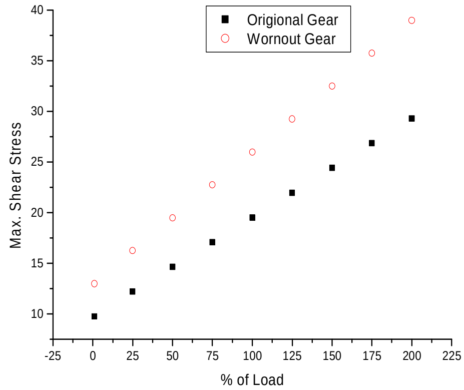
Based on the FE results, it is known that the maximum stress occurs at near the roots, and the maximum values by applying the define loads are shown in table III for original and worn-out tooth, respectively.

The computational model, for determining the remaining service life of gear has been taken based on FEM results for worn out gear tooth. As discussed above, since the maximum stress under loading is higher for original tooth than wear tooth loading, it has been seen as follows:

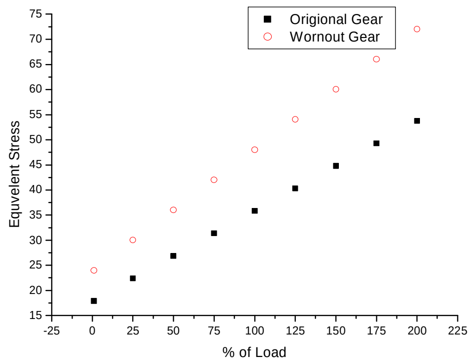
- The maximum principal stress of original gear tooth is more than wear out tooth shown in figure 9 (a).



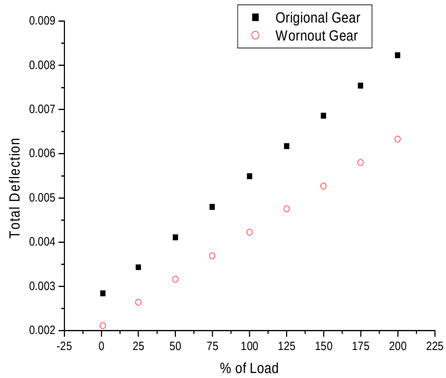
(a)



(b)



(c)



(d)

Fig. 9 (a) Influence between maximum principal stress and loads.
(b) Influence between maximum shear stress and loads.
(c) Influence between equivalent stress and loads.
(d) Influence between total deflection and loads

TABLE III.

TABLE IV. TOOTH STRESS RESULTS FOR ORIGINAL AND WORN-OUT SPUR GEAR TOOTH

Maximum Principal Stress (MPa)		**Maximum Shear Stress (MPa)**		**Equivalent Stress (MPa)**		**Total Deflection (mm)**	
Original Gear	***Worn Out Gear***	***Original Gear***	***Worn Out Gear***	***Original Gear***	***Worn Out Gear***	***Original Gear***	***Worn Out Gear***
19.410	13.432	9.7639	12.990	17.913	24.011	0.00284	0.00211
24.270	16.911	12.209	16.251	22.399	30.023	0.00343	0.00264
29.119	20.284	14.648	19.495	26.874	36.017	0.00411	0.00316
33.979	23.670	17.094	22.749	31.360	42.029	0.00480	0.00369
38.819	27.049	19.528	25.993	35.826	48.022	0.00549	0.00422
43.680	30.435	21.973	29.247	40.312	54.034	0.00617	0.00475
48.528	33.809	24.412	32.492	44.786	60.028	0.00686	0.00527
53.397	37.195	26.862	35.746	49.282	66.041	0.00754	0.00580
58.229	40.574	29.292	38.990	53.738	72.033	0.00823	0.00633

- The shear stress and equivalent stress are low for original gear tooth and higher for worn-out tooth gear shown in figure 9 (b) and (c) respectively.
- The total deflection is more for original gear tooth has been shown in figure 9 (d).

Consequently the stresses and deformation under compression loading should be reduced as small as we can, meanwhile the part should be made as wear resisting materials under the condition of meeting the operation requirement.

VIII. GEAR LIFE PRIDICTION

The aim of this work is to predict the remaining life of a machine component such as gear when it is subjected to wear. The gear service life under surface pitting and bending fatigue can be predicted with the help of contact stress and bending stress respectively. These stress values can be found using FEM. The methodology proposed for remaining life prediction for bending fatigue consists of

(i) Evaluation of principal bending stress (σ) on weared gear using FEM

(ii) Allowable gear bending endurance strength as given by AGMA is:

$$\sigma_{all} = \frac{S_t Y_N}{Y_\theta Y_z} \quad (1)$$

Where S_t is the allowable bending stress (N/mm^2), Y_N is the stress cycle factor for bending stress, Y_θ is the temperature factors and Y_Z are the reliability factor.

If S_F is AGMA bending stress safety, then it can be given as

$$S_F = \frac{\sigma}{\sigma_{all}} = \frac{\sigma Y_\theta Y_Z}{S_t Y_N} \quad (2)$$

Thus from Equation (2) one can evaluate Y_N for a given value of S_F. From Y_N one can find the value of number of load cycles (N).

Similarly the methodology proposed for remaining life prediction for surface pitting consists of

(i) Evaluation of von-mises stress (σ_c) on weared gear using FEM

(ii) Allowable gear contact endurance strength as given by AGMA is:

$$\sigma_{c,all} = \frac{S_c Z_N Z_W}{Y_\theta Y_z} \quad (3)$$

Where S_c is the allowable contact stress (N/mm^2), Z_N is pitting resistance stress cycle factor, Z_W is hardness ratio factor, Y_θ is the temperature factors and Y_Z are the reliability factor.

If S_H is AGMA wear stress safety, then it can be given as

$$S_H = \frac{\sigma_c}{\sigma_{c,all}} = \frac{\sigma_c Y_\theta Y_Z}{S_c Z_N Z_W} \quad (4)$$

Thus from Equation (4) one can evaluate Z_N for a given value of S_H. From Z_N one can find the value of number of load cycles (N).

IX. CONCLUSION

This paper presented the use of reverse engineering in assessing the gear tooth stress and in turn the remaining life of a wear out gear. 3D CAD geometric models were reconstructed before wear and after wear for gear using reverse engineering technology. Finite element numerical simulation is implemented for the rebuilt spur gear CAD model, and the peak values as well as the locations of stress and deformation are analyzed on gear tooth. With the help of FEA results and AGMA equations one can evaluate the remaining life of the gear, accordingly operating condition of the gear train can be modified and improved to get more remaining life of the gear train.

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