ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

PERFORMANCE ANALYSIS OF NANO REINFORCED POLYETHER ETHER KETONE (PEEK) GEAR

A Thesis submitted to the school of Mechanical & Industrial Engineering of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Mechanical Engineering (Mechanical Design Stream)

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Declaration

I the undersigned, declare that this thesis entitled **`PERFORMANCE ANALYSIS OF NANO REINFORCED POLYETHER ETHER KETONE (PEEK) GEAR`** is the result of my own research carried out under the supervision of Dr. Daniel Tilahun. It has not been presented in any from in any other university and all sources of material used for this thesis are accordingly sited and acknowledged. It is submitted in partial fulfillment of the requirements for the degree of Masters of Science in Mechanical Engineering, Mechanical Design Engineering at Addis Ababa University.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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Acknowledgment

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Abstract

Current research trend is shifted in finding better materials and enhanced material for gear application. Polymer nanocomposites materials are being used as alternative gear materials for the application of power transmission due to their numerous advantages. Polymer nanocomposites are lighter than conventional materials. They have high degree of stiffness and strength compared with high-density materials. In this study, best performing material is chosen scientifically comparing different materials that are used for power transmission that can sustain high cyclic load & wearing from recently developed literatures. Then the material property is predicted applying machine learning method. Chemical composition consisting of Polyether ether ketone (PEEK) polymer matrix composite material and the 4% nano filler multi-walled carbon nano tube (MWCNT), 3% Zicronia (ZrO_2) and 5% Silica (SiO_2) by weight is selected and the material mechanical properties is obtained from the trained machine learning model. Using the data obtained analysis of the gear with different loading condition is simulated with ANSYS software and the results are compared with recently developed gear materials for power transmission. The result shows that the addition of nano particles in PEEK polymer can improve the property of the material. The material gear life cycle is found to be one million cycles with loading condition of 1,450 rpm and 21 Nm torque and the maximum bending stress at this load is recorded for at the transient structural FEM analysis which is 75.22 MPa while in static structural FEM analysis is obtained 64.48 MPa. Whereas for contact and frictional stress close results are obtained. The polymer nanocomposite gear material is appeared to be potential gear material with enhanced material property, good strength and durability for the application of power transmission.

Keywords: PEEK Nanocomposite, ANN, Material Property Prediction, FEM, Gear

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Nomenclature

b	Half of contact width
C_H	Hardness ratio factors for pitting resistance
D_g	Gear pitch diameters
D_p	Pinion pitch diameters,
E_e	Equivalent modulus of material,
E	Young's Modulus
F	Force acting over contact length L
K_A	Application factor
K_g	Buckingham load stress factor
K_R	Reliability factors
K_T	Temperature factors
K_V	Dynamic factor
$K_{H\beta}$	Face load distribution factor for contact stress
$K_{H\alpha}$	Transverse load distribution factor
L	Contact length
m	Module
P_{max}	Maximum contact pressure
R_g	Radius of gear
R_p	Radius of pinion
R_e	Equivalent radius of curvature
R_1	Radius of cylinder 1
S_c	Allowable contact stress
S_H	AGMA factor of safety, a stress ratio
T_p	Torque on pinion
F_t	Tangential component of force
Z_B	Tooth contact factor
Z_E	Elasticity factor
Z_H	Zone factor
Z_L	Lubricant factor.
Z_N	Stress cycle life factor
Z_{NT}	Life factor for contact stress.
Z_R	Roughness factor
Z_V	Speed factor.
Z_X	Size factor.
Z_e	Contact ratio factor
φ	Pressure angle.
μ	Coefficient of friction
ν	Poison ratio

Chapter 1: Background

Among the various means of mechanical power transmission (including primarily gears, belts, and chains), gears are most compact and efficient power transmission. Their power transmission efficiency is as high as 98 percent.[1] The forces transmitted between meshing gears supply torsional moments to shafts for motion and power transmission and create forces and moments that affect the shaft and its bearings.

We know gears are so important in our daily life. Although it's not so visible. All automobiles including transports vehicles and plenty of other household equipment's use gears. [2]

The material used for the manufacture of gears depends upon the strength and service conditions like wear, noise etc. Gears may be manufactured from metallic, non-metallic materials or composite materials. Under the umbrella of composite material nano particles reinforced composite is becoming remarkable material for production of gears.

1.1. Types of gear materials

1) Metallic gears
   i) Metals and metal Alloys

   The metallic gears with cut teeth are commercially obtainable in cast iron, steel and bronze.

2) Non-metallic gears
   i) Composite gears

Composite gears refer to the use of composite materials for the production of gear.

   a) Fiber reinforced composite
   b) Particle Reinforced composite

   ii) Plastic\Polymer Gears

Plastic or polymer gears are manufactured by machining or an injection molding process from any engineering thermoplastic polymer.

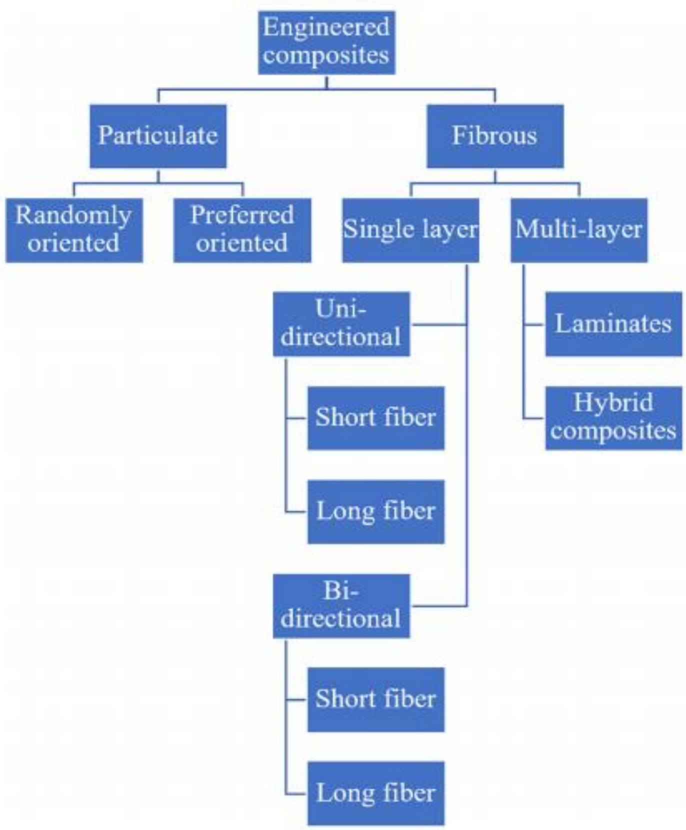


Figure 1- 1 Classification of composites according to orientation of fibers/particles and numbers of layers [3]

1.2. What is nano-composite?

Researchers have found niches in new technologies and/or have satisfactorily replaced other engineered materials. It has been found the combination of materials can improve the properties of materials. Engineers obtained a fundamental understanding of materials behavior in heterogeneous materials so that further improvements can be achieved.

The nanoparticle includes the particles having size between 1 and 100 nm. [4] These particles have different properties at their atomic level due to their size. Nanoparticles have those chemical and physical properties which makes them very different from that of the corresponding bulk materials due to their small size and large surface to volume ratio.

Nano composites

Nano composites are those composites in which one phase has Nano scale morphology like nanoparticles, nanotubes, or lamellar nanostructure. The idea behind Nano composite is to use building blocks with dimensions in nanometer range to design and create new materials with unprecedented flexibility and improvement in their physical properties. [4]

By creating composite materials, material property combinations and ranges have been expanded and continue to be so. In general, any multiphase material that demonstrates a sizable amount of the traits of its two constituent phases so that a superior synergy of traits is realized is thought to be a composite. [7] This combined action concept states that improved property combinations can be created by carefully combining two or more different materials.

In this application, a composite is a multiphase substance that has been created artificially as opposed to organically. Additionally, there must be a clear contact between the constituent phases and they must differ chemically. Because their various phases are a result of natural events, most metallic alloys and many ceramics do not satisfy this criterion.

The characteristics of the constituent phases, their proportional amounts, and the shape of the dispersed phase all influence the properties of composite materials. In this sense, "dispersed phase geometry" refers to the size, distribution, and orientation of the particles as well as their shape.

Composite gears provide a ton of promise for high-tech applications and special benefits over metal gears, including low cost, low weight, great efficiency, and operation in silence. Materials for new technologies must perform better than those used in conventionally produced components. Metal gears are currently being replaced with nano reinforced composite gears for applications ranging from high power transmission to low power precision motion. [8]

1.3. Machine learning process to predict material property

Using composite and advanced materials in engineering industries requires complicated analysis and modeling which in most cases computer software runs the analysis. In the case of a thick laminate or a structure it would be a time-consuming procedure to predict the mechanical and thermal properties of the desired laminate or structure by ply-by-ply approach. The computational complexity of this approach scales exponentially with the number of constituting elements. [5]

Machine learning aims at developing algorithms that can learn and create statistical models for data analysis and prediction. The ML algorithms should be able to learn by themselves based on data provided and make accurate predictions, without having been specifically programmed for a given task. [5]

Implementing a Machine Learning Methodology

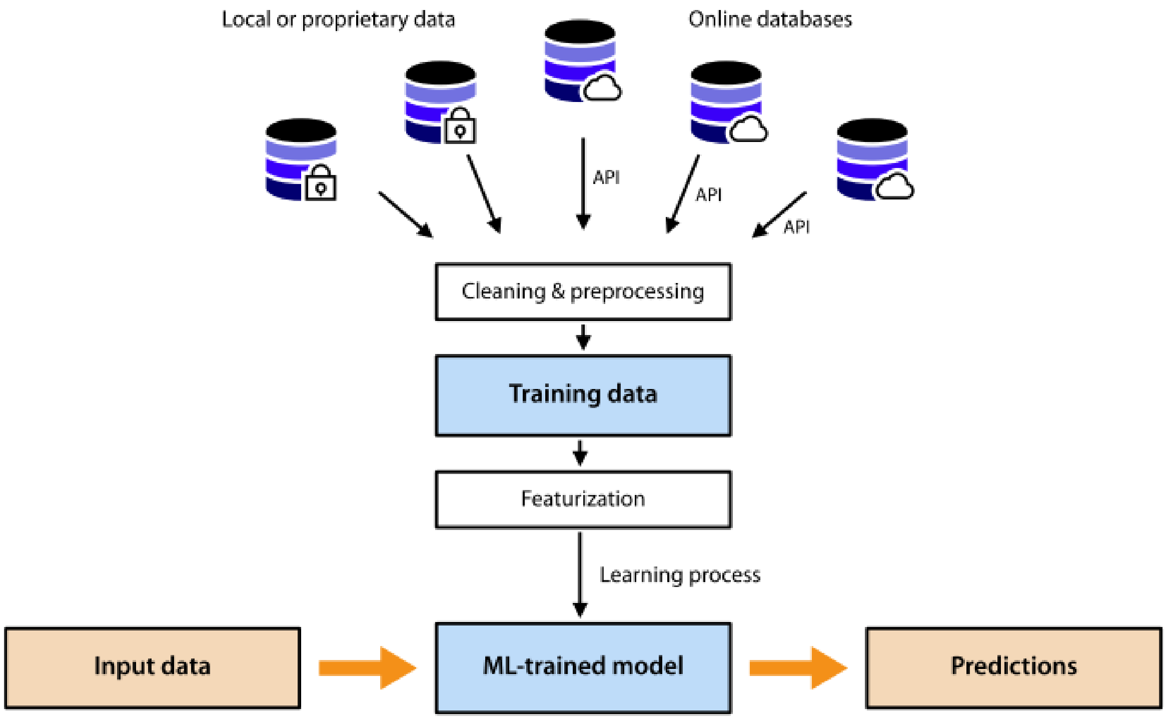


Figure 1- 2 Simplified overview of a machine learning workflow. The machine learning model is trained on input data gathered from multiple databases. Once it is trained, it can be applied to make predictions for other input data [5]

Composite gears are increasingly being used from low to medium power transmission systems. There is still the gap of knowledge of applications of composite materials in high power transmission systems. Not enough study is conducted in the use of cheap and abundantly available and recyclable particles (reinforcing materials of natural origin) for wide application. Therefore, attentions should be given for the investigation of new enhanced performance composite gears.

The application of composite material is limited in automotive component particularly in engine environment. By conducting study on tribological behavior analysis in tis extreme condition, alternate material development and application of those material will enable full exploitation of composite materials. As a result, the application of enhanced composite material will decrease weight and fuel consumption of the vehicle, because most vehicle weight is in the engine and power transmission component, which results in the development of light and green technology.

From this research suitable Nano particle type with effective concentration for high power transmission gear will be selected and performance will be compared with conventional manufactured high power transmission gear.

1.4. Statement of the Problem

The application of composite material is gaining the attentions of researchers due to their numerous advantages over metallic materials.

Researchers are now putting their effort to find better materials every day and the advancement in composite materials and their application is developing. More advantages of composite materials are of great interest, particularly in sever environment application of engine and power transmission like that of gears. Systematic selection of gear material that can handle specific speed and loads with smother and quitter operation needs exhaustive study and experiments in order to find high performing materials.

The existing nanocomposite gear application is limited because nanocomposite gear fails at high load and high speed operating condition. Failure is mainly caused by gear tooth wearing (adhesive and abrasive wear), gear tooth bending/deformation due to the cyclic load.

This problem can be solved by developing gear material that can withstand failure against bending of gear tooth and wearing. This can be achieved by developing new enhanced material that constitute higher dynamic characteristics (tensile, compression and bending). Reinforcing polymer materials with nano particles improves the property of the material significantly as reinforcing particles approaches to nano scale level. In order to study new and better material, simple and cheaper performance testing and material prediction tools are important that can handle higher load without failure.

This research employs the use of artificial neural network (ANN) method to predict the selected nano particle reinforced polymer gear material and analysis of the gear and failure mechanism will be performed in an attempt to put in use of nano particle reinforced composite gears for power transmission.

1.5. Objective

1.5.1. General Objective

The main objective of the study is to investigate the performance of gear developed from nano particles reinforced polymer material for the application of power transmission.

1.5.2. Specific objectives

The specific objectives of this research include:

- ✓ Selection of optimum material (chemical composition & weight percentage) and predicting of material properties for nanocomposite gear employing artificial neural network (ANN) method.
- ✓ Examine the loading capacity and strength of gear tooth analytically and using ANSYS workbench software.
- ✓ Examine the tribological properties (contact analysis) of nanocomposite gear using ANSYS workbench software.

1.6. Scope and Limitation of the research

The scope of the research is determining or selecting of materials from experimental results conducted by different researchers and by applying machine learning process prediction of characteristics properties of nanocomposite gear material. Then the material is tested for the loading capacity by modeling and simulating using ANSYS Workbench software.

- ✓ The comparison of nanocomposite material and conventional gear material data is obtained from literatures of experimental research.
- ✓ While modeling gears the conventional procedures as that of metallic gear is used to produce geometric features.
- ✓ Thermal effect in gear application and the geometry of the reinforcing particle effect is not included in this research.
- ✓ For ease of modeling and simulation purpose spur gear is selected as test subject.

1.7. Thesis Organization

This research paper focuses on the development of gear material from polymer material reinforced by nano particle and analyze the performance of the material in order to use it in medium or higher power transmission gear. This research paper comprises of eight chapters. Chapter 1 Introduces the background of gear materials and discuss the overview of nanocomposite materials and their application in gear material. In addition, an introduction of machine learning process and the prediction process are discussed in this chapter. The research objectives, Statement of the Problem, Scope and limitations are also discussed. Literature reviewed all relevant research papers regarding nano composite materials, their application and failure modes, comparison of materials and selection of material is investigated in chapter 2. Chapter 3 shows the methodology of the research which includes the material property prediction and method utilized to predict material property and the finite element analysis process are shown in detail. Results obtained from machine learning tool and finite element analysis are illustrated and discussed in chapter 4. Additionally, comparison of this research results from different references is conducted. Finally, chapter 5 concludes the general findings of the thesis report and give recommendations based on the finds and propose future research works to pursue.

Chapter 2: Literature Review

The literature reported in this portion investigates different nanocomposite materials and their performance for the application of different purpose and specifically for gear material. It also reviews failure mechanism of composite gears material (wear, fatigue and high temperature), the effect of manufacturing method and gear geometry in addition to selection of gear material with the use of ANN tool and prediction of their properties and accuracy from different published articles and journals is articulated hereunder.

2.1. Nanocomposite materials

A study was done to determine how the presence of the layered nanoclay Cloisite 20B affected the tensile and compression characteristics of the glass-fiber reinforced polymer (GFRP). The impacts of the three nano clay weight percentages—0.5 weight percent, 1 weight percent, and 2 weight percent—on the mechanical characteristics of the composite material were investigated. The result of adding 1 weight percent of Cloisite 20B nano clay to epoxy was an increase in GFRP's tensile strength of 6.75% to 7.59%. [9] Additionally, a significant amount of Nano fillers were used, which improved compressive strength. The action of the nanoclay fillers slowed the onset or spread of cracks.

Another study shows that the overall performance of polymer/acetal gear can be enhanced by reinforcing it using nanosilica particles. Numerical Results from Abaqus/CAE is used to analyze the nano composite gear wear, temperature resistance, and fatigue life. Thermal and mechanical property of acetal (polymer) has improved significantly by the addition of only 4.5% volume weight addition of nano-silica. [10]

A literature review conducted on tribo-mechanical properties of nanoparticulate-filled nylon composites showed that the mechanical and tribological properties of nylons are enhanced by the various micro- and nano particulates fillers. [3] The coefficient of friction of nylons is improved and wear rates are decreased by the particulate filler reinforcements. Mechanical properties like Tensile strength, hardness, and impact strength of nylons are improved.

Experimental research on fabrication of Acetal reinforced graphene nanocomposites and evaluation of their mechanical and tribological properties has been conducted. Based on the experimental results the tensile strength, young’s modulus, flexural strength and flexural modulus were improved for 1.5wt% of composition and elongation at break and impact strength were decreased when compared to pure Acetal copolymer. It is also observed that the tribological properties obtained, wear rate and coefficient of friction were considerably decreased compared to pure acetal. Investigation by FEM for the performance evaluation of nano particle graphene reinforced acetal gear 1.5wt% filler, loading and the results has been compared with metallic gear (Cast Iron) and also with a plastic gear made up of polycarbonate.[11] When compared with polycarbonate gears the stress levels generated are much lower thereby ascertaining the superiority of acetal reinforced graphene nanocomposites gears for tribological applications. The von–Mises's stress and deformations are decreased for graphene/Acetal gears as compared to polycarbonate gears.

Although there are different types of nano filler particles, property enhancer fillers were listed specifically for the application of composite gear. Nano clay closite 20B shows improved mechanical strength, while nano silica is good for thermal and wear resistance. But grapheme seen to show advantageous in tribological and mechanical strength and durability of the materials.

2.2. Performance of nanocomposite gears

Experimental study is used to test nanocomposite gears made of polyoxymethylene (POM) and having various fractions of calcium carbonate nanoparticles (0, 3, 6, and 9 wt%). The POM/3 wt% $CaCO2$ nanocomposite gear had a maximum gear life of around 98,000 rotations and a minimum gear life of about 48,000 revolutions in clean POM gears. [12] It was discovered that nanocomposite gears performed better than pure POM gears under similar operating circumstances and had lower gear tooth temperatures.

Reinforcing polyester resin with melon shells powder (850-micron size) to form a composite material spur gears through an experimental and analytical approach was studied. The particulate Citrullus Lantus (melon) shell (CLS) reinforced polymer composite was modelled for gear application. The geometric model of a typical spur gear was modeled and simulated.85.08 MPa recorded as the tensile strength value for the Particulate CLS Reinforced Composite, which is lower than that of cast steel (540 MPa) used to benchmark the spur gear design. However, the obtained tensile strength for the PCLSRC can be used to design and develop spur gears operating within the range of≤ 85.08 MPa loading condition.[13] The results showed that for a 5% weight fraction of melon shell in the preparation, the material gave satisfactory performances for spur gear application where loading condition and torque requirement is less than 90.3 MPa and 14 N-m, respectively.

Composite material with30% glass filled Polyamide 66 and 30% glass filled Poly-ether-ether-ketone materials were selected for the study.[14] Wear tests of the spur gear pairs and the experiment spur gear tooth were performed on a FZG. The FZG test machine is a power-circulating test machine with test spur gear tooth wear apparatus. Mean temperatures of PEEK GF30 and PA66 GF30 gear tooth were measured with Impact Infratherm Pyrometer 510-N infrared thermometer at a distance of 8 mm.

Results showed for ***PA66 GF30*** the increase in temperature for these gears in the range of 62 ^{o} C to 74 ^{o} C for the applied toque of 2N-m to 4.5 N-m, these gears are more sensitive to torque variation and speed variation. As the applied torque on the gears was increased, the tooth temperature also increases drastically. The gear with high load & high speed was failed after 1 X

10^5 revolutions. After damages occurred, gear profiles could not mesh each other exactly, and tooth temperature decreased due to the failure of contacting. For PEEK GF30. as applied torque acting on gear teeth increases, the temperature of gear tooth at the pitch point is also increases. The increase in temperature for these gears is in the range of 54 ^{o} C to 59^o C for the load toque of 2N-m to 4.5 N-m.[14]The article concluded as at high torque and high speed, the gears of PA66 GF30 material are failed. And in regard to wear the comparative results of PA66 GF30 and PEEKGF30 gears shows that, the specific wear rate of PA66 GF30 is much higher than PEEK GF30 at all torques and speeds. Therefore, the torque transmission capacity of PEEK GF30 is higher than PA66 GF30.

Another research deals with the design and optimization of the differential gear box through use of composite material.[15] Glass filled polyamide in particulate form E-glass/Epoxy composite is used for differential gear box (bevel and spur gears) having better tensile strength (38.1 Mpa), recyclability, low density (840 Kg/m^3), high creep resistance, fatigue strength, low Von-Mises Stress, high impact strength, less friction and low cost. The solid modelling is done by using SOLIDWORKS at peak torque of 130Nm at 5000 RPM. The torque loading at 130Nm under Static analysis is performed on the gear using Ni-CR steel, malleable cast iron, aluminum alloy and glass filled polyamide using ANSYS 14.5.

Materials	**Stress (N/m2)**	**Strain**	**Displacement (mm)**	**Density (Kg/m3)**
Ni-Cr steel	**6.193×10^8**	**2.207×10^{-9}**	**1.67×10^{-6}**	**7800**
Malleable Cast Iron	**4.067×10^8**	**1.341×10^{-3}**	**1.280**	**7300**
Aluminum alloy	**3.865×10^8**	**3.608×10^{-9}**	**3.771×10^{-6}**	**2600**
Glass Filled Polyamide	**5.805×10^8**	**6.257×10^{-8}**	**5.411×10^{-5}**	**1840**

Table 2- 1 Comparison table of Glass Filled Polyamide with metals[15]

The analysis shows the Glass filled polyamide in particulate form E-glass/Epoxy composite is suitable material for differential gear with lower stress and density in result it reduces the weight of the differential gear box, hence increasing efficiency.

In a study carried out, composite material of compositions having HDPE (High Density Polyethylene) as matrix, carbon fiber powder as reinforcement and silicon carbide powder as filler are fabricated using vertical injection molding method.[16]Evaluation Mechanical characteristics of the prepared composite materials this includes its tensile and flexural strength is carried out and optimum composition of HDPE reinforced composite with carbon fiber powder as reinforcement and silicon carbide as filler is calculated. After modeling in CATIA V5, numerical analysis of composite material spur gear in ANSYS workbench in static loading condition is conducted. From experimental results and numerical analysis of HDPE composite material spur gear it is conclude that replacement of cast steel spur gear is possible with HDPE composite spur gear (with best composition of HDPE (84%) +carbon fiber powder (10%) + silicon carbide (6%)) alternative to cast steel spur gear up to torque of 140Nm and speed of 2500Rpm. Additionally, it is inferred Strength of material is good and it can be used as alternative for metallic gear as weight is reduced drastically.

Comparative results of neat composites and nano reinforced composites, nano particle reinforced resulted significant improvement. The use of different nano particle materials is studied with optimized constituent composition percentage. Silicon carbide is suited mainly for its wear and thermal resistance and mechanical property improvement. Materials reinforced with nano particles results comparative performance with that of conventional metallic materials.

2.3. Failure modes of composite gears

Composite gears fail due to breakage and they are classified into three; the first mode involves a sudden breakage occurring at the root due to impact loading of the gearing. [17] The second failure mode due to breakage is fatigue at the tooth root due to constant repeated loading. And finally, the tooth corner breakage failure mode is mostly due to the uneven distribution of loads from axis misalignment.

On experimental study conducted, composite gears (55% nylon, 30% glass fiber and 15% PTFE) fail in two ways: one by fatigue, the other by wear. [18] Gear wear rate will increase dramatically when the load reaches a critical value. The gear surface wear slowly with a low specific wear rate if the gear is loaded below the critical one. From the study, the reason of sudden increase in wear rate is due to the gear operating temperature reaching the material melting point under the critical load condition.

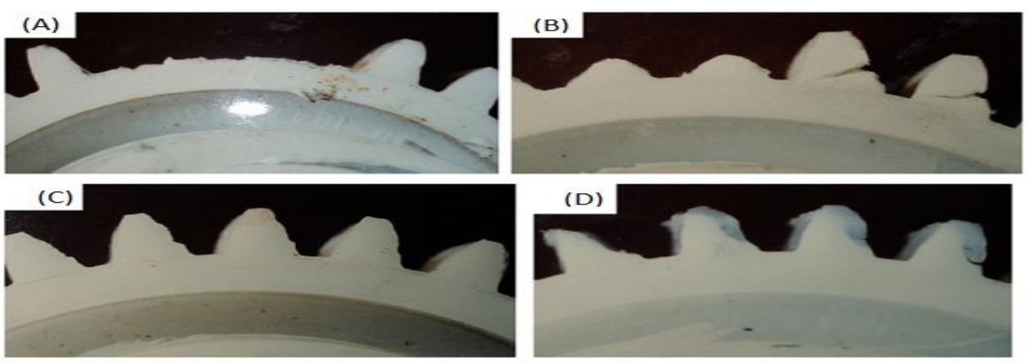


Figure 2- 1 Acetal gear failure forms (A) at 500 rpm and (B) at 1000 rpm and wear forms under loads of (C) 7 Nm and (D) 10 Nm.[18]

FEM is used in the study to produce reinforced polyoxymethylene with neat polyoxymethylene (POM) gear and $CaCO_3$ nanoparticles. The driver gear experiences greater tooth deformation, temperature, and wear than the driven gear due to the higher tension placed on its teeth. The wear on the composite gear tooth that contains 3 wt% $CaCO_3$ is found to be the least. The clean POM gear's surface wear shows heavy adhesive wear and light abrasive wear. POM nanocomposite gears with 3 and 6 wt% nanoparticles have substantially smoother worn surfaces than a clean POM gear. [12] The smoothest worn surface is found on POM/3 wt%CaCO3 nanocomposite gear, where only moderate abrasive and adhesive wear is seen.

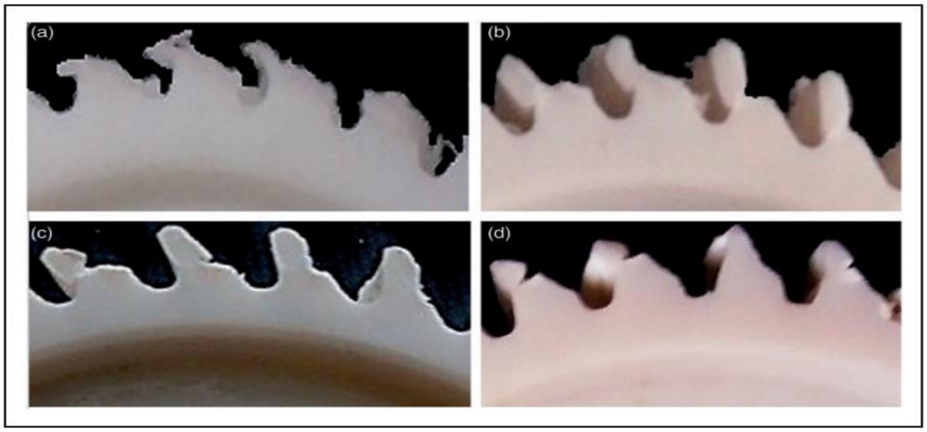


Figure 2- 2 Gear teeth failure: (a) POM gear (at 48,000 revolutions), (b) POM/3 C gear (at 98,000 revolutions), (c) POM/6 C gear (at 76,000 revolutions),and (d) POM/9 C gear (at 54,000 revolutions)[12]

In regards to thermal stability, the decomposition temperature of neat HDPE is lower than the composition of HDPE/MWCNT, demonstrating enhancement of nanocomposites' thermal stability ascribed to the addition of multiwalled carbon nanotube (MWCNTs). By increasing the amount of MWNTs, the residual weight of MWCNT/HDPE nanocomposites increased steadily. The decomposition of the neat HDPE and the MWCNT/HDPE nanocomposites started at around 400 ◦C and continued up to nearly 500 ◦C. The weight loss of neat HDPE at 782 ◦C is about 85%. In contrast, in MWCNT/HDPE nanocomposites, the weight loss is between 52–60%. Hence the retention of 25%–33% is achieved, indicating improved thermal stability and resistance to thermal degradation in the nanocomposites.[19] Hence, it is conclusively evident that the addition of MWCNTs to HDPE has significantly improved the thermal stability.

The tensile and impact test conducted, the yield strength increased almost linearly as the nanofillers are introduced in HDPE up to a concentration of2 wt.%, confirming that the nanofillers enhance the tensile properties of polymers. MWCNT/HDPE nanocomposites at different concentrations. The addition of nanofillers steadily increased young's modulus up to a weight fraction of 1.5%The abrasion test of neat HDPE and its nanocomposites with different concentrations of MWCNTs shows that the wear loss of MWCNTS/HDPE reduced substantially with the increase of the concentration of MWCNTs.[19] This reduction in weight loss is synchronous with the enhancement of hardness.

Gear damage mechanism

As a result of the elevated torque and heat gathered at the surface, the thermal conductivity decreased. Therefore, the gear damaged because of the thermal bending phenomenon resulting in tooth deterioration accumulated on the root and tip area. The high temperature caused by the applied torque led to teeth deviation and teeth reduction in pitch grooves' proximity. The damage mechanism of gears changed from thermal bending (in neat HDPE) to slight tooth wear for 2 wt.% MWCNT/HDPE gears. Further addition of multiwalled carbon nanotubes (MWCNT) in 2.5 wt.% MWCNT/HDPE, at a torque of 10 N-m, partial thermal softening signs occurred followed by teeth abrading along face width.[19] The thermal bending at the flank and profile links of the tooth accelerated as a result of the thermal effects of the applied torque. As a result, compared to clean HDPE, the addition of MWCNT marginally altered the damaging mechanism. There were signs of tooth fracture, deflection, and partial bending. However, due to compromised thermal and dimensional stability, only modest tooth deflection signals and no overt thermal tooth bending were seen in 2, 2.5 wt.% MWCNT gears. As a result, the amount and distribution of MWCNT in HDPE nanocomposites have a significant impact on their gear efficacy.

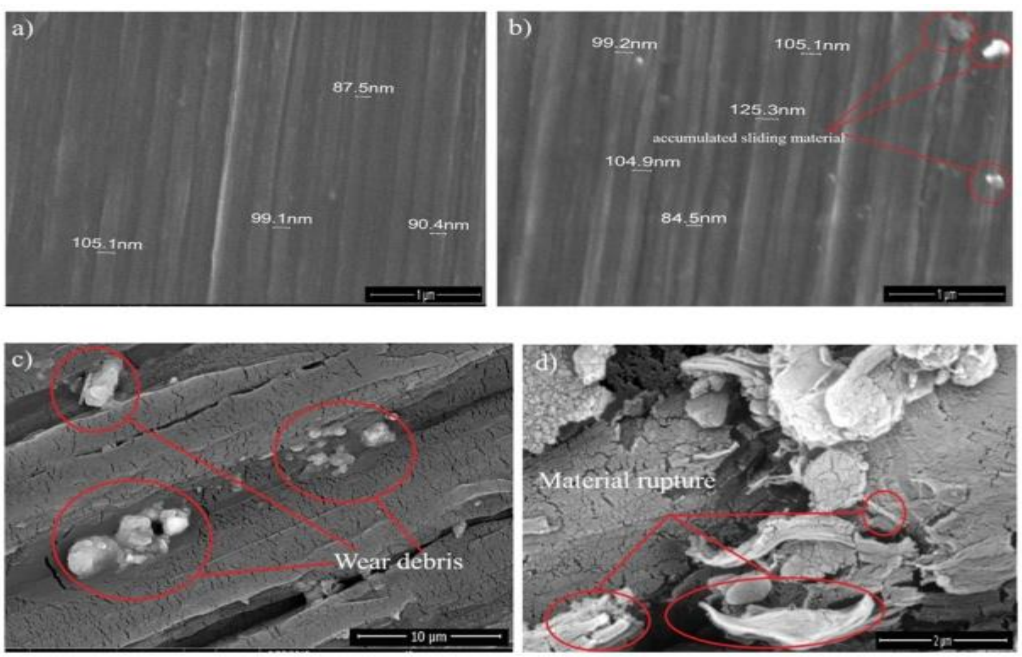


Figure 2- 3 SEM of 2 wt% MWCNT/HDPE spur gear surface: (a, b) @5N-m. (c, d) @10N-m[19]

Literatures reported that failure of nano composite gear can occur due to fatigue, wear and temperature. The main Failure modes of composite gears are excessive tooth wear, fatigue (tooth cracking) and tooth deformation. The failure mechanism depends on the testing conditions (load, speed and temperature) and material combination. Wear is mainly caused by worn surfaces of nanocomposite gear that minor abrasive and adhesion is seen. Wear damage is measured by weight loss from the total material. Failure due to high temperature is caused by thermal softening which leads to thermal bending.

2.4. The effect of gear geometry on the performance of composite gear

Laurenţia A. investigated the influence of the modified tooth geometry of the curved face width spur gears on the sliding velocity, as one of the main causes of frictional losses that increase the gear temperature and also considers the special meshing conditions of plastic gears. From the study it is found that Polymer gear teeth, with a relatively low young's modulus, will deflect elastically under load, the deflections being larger than those experienced by metal gears. As a result of the applied load, a premature engagement takes place, as well as a delayed disengagement.[20] Hence, the contact point for a plastic gear train is differently positioned compared to the ideal rigid gear pair and is influenced by the amount of tooth deflection. It is concluded that the real sliding velocity considers the influence of both the gear geometry and tooth deflection. It was found out that the sliding velocity is mainly influenced by the gear geometry. The gear tooth deflections do not have a significant influence on the sliding velocity - they reduced its variation compared to the ideal calculation.

2.5. Other composite gear materials

Amarjeet R. Studied Composite gear implementation by replacing metallic gears with thermoplastic gears in the gearbox of Bajaj Sunny moped. The material selected is thermoplastic materials viz. cast nylon, NylonDOS+2 for the production of plastic Gears, and designed with same power transmission as that of metallic Gears.[1] The gears are tested for displacement, strain and stress and simulated using CAD modelling and FEM for analysis of the plastic gear and its material. Result shows that Plastic Gears can be applicable in the gearbox of two-wheeler low power gearbox of Bajaj Sunny moped.

Utkarsh.M.Desai et al study's involves developing GF 30 PEEK composite spur gears to replace alloy steel spur gears. [21] The outcome of the stress analysis demonstrates that the GF 30 PEEK spur gear is stronger than the alloy steel spur gear. Additionally, the density is lower than alloy steel. As a result, it is determined that the GF 30 PEEK (composite) spur gear can replace the alloy steel spur gear due to its high strength, low weight, and damping properties.

V.R Gajender research with the objective to design spur gear using advanced modelling software (Solidworks) and is meshed and analyzed using analysis software by the application of torque load. The study in stress distribution and weight reduction of spur gear for composite materials and cast steel has been done. [22] The analysis of both composite materials and cast steel are analyzed in the application of gear box which is used in automobile vehicles. From the analysis results, it is concluded that, the stress induced, deformation and weight of the composite spur gear is less as compared to the cast steel spur gear and followed by Glass filled polyamide. Therefore, Composite materials are capable of using in automobile vehicle gear boxes instead of existing cast steel gears with better results.

The development of static bending stress in a pair of gear transmitting 4.1 kW power, with a speed of 30 rpm and 1306 Nm torque is investigated and the static stresses developed on gear tooth material at low speed and high torque for two different materials; C45 steel and high-density polyethylene (HDPC) is presented.[23] For the C45 steel and HDPE made spur gear at the starting condition a turning moment of 1306 Nm is applied on the gear teeth and this amount of torque was transferred from pinion to gear. From both results, it is seen that maximum bending stress occurs at the base of the root and at the point of contact. The results of bending stress distribution, modal displacement and modal frequencies were finally compared for both cases of the metallic and the HDPE made gear pairs. And HDPE made gear have shown comparable result with that of C45 steel made gear.

The evaluation of the influence of speed and load of wear behavior of polyamide 66 reinforced with increasing amount of glass fiber under dry conditions is conducted and Wear tests on PA66 against EN8 steel disc is carried out on pin on disc arrangement.[24] Tribological tests are performed at room temperature and mechanical properties like tensile test and hardness tests are performed according to ASTM standard. Wear formation such as tooth fracture, tooth deformation, debris and weight loss were observed on bio-polymer spur gear.

2.6. Fabrication of nanocomposite gears

The multiwalled carbon nano tube (MWCNT) -epoxy nanocomposite is produced with high intensity ultrasonic waves created alternative high and low pressure inside the mixture that formed small vacuum bubbles. Simultaneously, magnetic stirrer was used with speed of 250 rpm that provided agitation to the MWCNTs and mixed them with adhesive mixture. Then, the aliphatic hardener of 1/3rd weight of epoxy resins thoroughly mixed inside the MWCNT- epoxy mixture and subsequently, the vacuum degassing process was used to remove the air bubbles. [25]

Vacuum assisted resin transfer molding was used to create nanocomposites (VARTM). The method involves applying an appropriate resin under vacuum into a sealed vacuum bag made of pre-laid composite fabrics (in this case, mats of glass fiber and carbon nano paper sheet oriented as needed). [6]

The mixture of matrix and nano particle is essential for the performance of the gear. There have been many inventions that help thorough mixing of composite constituents. In-situ polymerization, melting compounding, mechanical stir, melt intercalation, ultrasonic waves and magnetic stirrer are some of the applied methods to produce nano composites in different experimental research and studies. Of all type ultrasonic waves and magnetic stirrer have resulted a better method to mix composite constituents to create effective coalescence that disrupts and breaks agglomerates to produce uniform mixing.

2.7. Possible area of application of nanocomposite gear

Gear rattling noise in mechanical system like that of mass balance gears, cam gears, pump and accessory drives became notable in Noise Vibration and Harshness (NVH) issue. Automotive industry manufacturers are constantly looking for ways to reduce noise and vibration as well as improve efficiency.

In order to comply with engine vibration dampening and noise reduction regulations, the balancing shaft counterweight is a typical mechanism for reducing the engine's moment of inertia. The performance of the balance shaft's vibration dampening mechanism is directly influenced by factors such the structure shape, material, mass, and inertia of the gears, and the efficient use of the balanced system's assembly space is taken into account. It is necessary to minimize the quantity and bulk of pieces in the balance mechanism's design. [81-84].

In a conducted study, it shows the benefits of polymer gear offering a 3 dB (~50%) enhancement in NVH, a 68% weight reduction resulting in 78% reduction of the moment of inertia and therefore 9% less torque required to operate compared to a cast iron gear set for an engine mass balancer module. [86]

Several studies done with high performance polymer (PEEK) gears to clearly show the potential for NVH and efficiency improvement for applications in modern downsized combustion engines.

Nanocomposite gear can replace the existing metallic gears due to their good low weight low noise and competitive performance with that of metallic ones. Some of application area in automotive engine are listed as:

- Oil pump gear in automotive engine
- gears in the mass balance system
- other miscellaneous power transmission use like windshield wiper

In gear application the loading condition vary greatly. Different experimental researches conducted uses different sets of loading conditions. In this study, the gear being developed is assumed to be in use to withstand sever loading condition for power transmission gear application.

In order to understand the sever condition of polymer nanocomposite gears, different research is conducted from different sources of experimental research. The obtained data is tabulated in the tale below.

Table 2- 2 Loading condition of different nanocomposite gears

No	Gear Material	Experimental loading condition	Ref.
1	MWCNT/HDPE nanocomposite spur gear	rotating speed 1500 rpm and 5 to 10 Nm applied moment	81
2	nanocomposite MLNGPs/PA6 spur gear	rotating speed 1400 rpm and twisting moment 13 and 16 Nm	35
3	Clay nanocomposite PA6 spur gears	run at a speed of 1200 rpm at a torque levels (1.5, 2.0 and 2.5 N m)	83

4	CNTs and PTFE nanocomposite POM spur gears	rotational speeds (500, 750, 1000, and 1500) rpm torques at (1, 1.5, 2, 2.5 and 3) Nm	84
5	carbon black nanocomposite polyacetal spur gear	rotating speed 1500 rpm and torques 6 and 8 Nm	85
6	nano-CaCO3, nanocomposite Polypropylene (PP) PA6 spur gear	rotation speed of 645 rpm and applied torque of 8.9 Nm	38
7	carbon nanotube–polypropylene spur gears	Rotational speed of 800 rpm applied maximum torque 4.5 Nm	41

The engine mass balance system operates in an environment where temperatures range from −40°C to 150°C. The gears in the mass balance system rotate as high as 1450 rpm with a peak torque from 20 - 25 Nm. Chemical resistance is an important attribute required for the gears as they reside in an oil bath and are also subject to small amounts of gasoline and diesel fuel. [85] This is where sever condition of engine environment where polymer nanocomposite can replace metallic gears.

It can be suggested that nanocomposite gear can be applied in the medium load range of engine environment.

2.8. Comparison of nanocomposite gears Material Performance

Nanocomposite gears can be manufactured from different types of material combination. Manufacturers use different sets of materials as per the quality aspect, performance aspect and tribological aspect for different application of the gear. Different manufacturers started using PEEK material by replacing metallic gear of oil pumps and balance shaft transmission gear.

PA and POM are currently the most widely used plastics for gear wheels, accounting for more than 85%. They have proven to be superior to other gear plastics (e.g. polycarbonate, polyethylene), especially for power transmissions. At higher ambient temperatures, the load carrying capacity of PEEK gears is superior to POM. It also has good friction and wear properties. [40]

Experimental research detected more pitting in grease-lubricated steel/PEEK gearboxes compared to steel/POM gearboxes. The reason for this is that the higher modulus of elasticity of PEEK, causes a higher flank pressure with the same line load. Despite lower strength values, POM wheels can achieve a longer service life than PEEK wheels. [41]

Five polymer materials have been used to manufacture the gears for a study. That is: PC (polycarbonate); POM (Polyoxymethylene); HDPE (high-density polyethylene); PA (Polyamide, nylon 46); and PEEK (Polyether ether ketone, or PEEK650). Incremental load is applied until a rapid wear rate increase is observed and the experimental test is completed. All tests were run at a constant speed of 1,000 rpm. The gears were loaded at 3Nm for one hour, after which the load was increased to 4, 5, 6 and 7Nm for one hour running under each load. Under 7Nm the polycarbonate gears failed due to pitch fracture. The observed critical torques for each gear pair are about 6 Nm for polycarbonate (PC); 8 Nm for POM; 8.5 Nm for PA; 11 Nm for PEEK; and 4.7 Nm for high-density polyethylene (HDPE). [42]

Above the critical torques, the polycarbonate gears failed due to pitch fracture; the POM gears failed due to thermal wear (the tooth surface maximum temperature reaching the POM material melting temperature; the PA and PEEK gears failed due to excessive surface wear; and the HDPE gears failed due to large deformation. The large deformation failure of the HDPE gears was expected, given its low modulus of elasticity (approximately one-third of the other polymers considered). [43]

It can be observed that PEEK attaints the highest critical torque of 11 Nm which shows the best performance from other types of material.

Appropriate fillers can also be added to improve the tribological characteristics and mechanical features of the material. Traditionally, several approaches are undertaken for strengthening PEEK through incorporation of filler particles and fibers realizing the high-performance characteristics of PEEK that may not be accomplished due to scuffing and abrasion of PEEK-metal contacts in specific tribo-systems. In applications with long term heat exposure, PEEK is capable of handling around 500 ◦F and much higher temperature during short term exposure. This temperature is far beyond the capability of most polymers.

The balanced wear resistance of PEEK can be matched by very few polymers. Effects of fatigue and abrasive wear as well as friction are overcome by the properties of PEEK by its resistive nature and low friction coefficient. At low velocity and maximum stress levels, the wear resistance and fatigue resistance of unfilled PEEK is exceptional. Better wear rate and lesser friction coefficient are provided by 20% PTFE filled PEEK material.

In extreme wear applications, the low mating part wear and high pressure-velocity (PV) performance makes it an ideal choice. Remarkable heat dissipation, high ductility and abrasion resistance are some of the significant properties of this material. [44]

PEEK is a high-performance thermoplastic material with a special blend of stiffness & toughness. The recent addition of nanofillers to these materials to increase their usability in cutting-edge technological applications represents an important advancement in their development. Compared to clean polymers, composites containing carbon nanofillers exhibit significantly increased heat stability and mechanical performance increases. The tribological properties of the matrix, particularly the coefficient of friction and wear resistance, are greatly improved by the incorporation of inorganic nanoparticles like WS2, SiO2, or Al2O3. [45]

The incorporation of Si_3N_4 nanoparticles into PEEK caused a significant improvement in the tribological characteristics, resulting considerably in decreased frictional coefficient and wear rate.

The tensile stiffness and strength of the carbon nanofibers (CNF) filled PEEK nanocomposites increased linearly with increasing CNF content up to 15 weight percent, while the tensile ductility was maintained up to 10 weight percent CNF. PEEK composites loaded with 86 nm ZrO2 nanoparticles started to have inferior wear resistance than empty PEEK. The PEEK-based nanocomposites can increase their hardness, elastic modulus, and tensile strength by 20–50%

without sacrificing tensile elongation, regardless of whether silica or alumina particles are placed in them. [46]

Polyether ether ketone (PEEK) composites were developed using Fillers fly ash of particle size 44 micrometer and mica (wet grinded) of particle size 44 micrometer. The rate of decrease in elongation at break of PEEK fly ash composites were higher than the PEEK mica composites shows that the brittleness of composite increases with the fly ash content. Also, the toughness decreased with increasing fly ash content. [47]

The findings show that the presence of silica nanoparticles has a clear impact on the wear and friction characteristics of PEEK/CF/nano silica composites. While the specific wear rate increases with increased nano silica loading, the friction coefficient falls as the amount of nanofiller increases. In comparison to PEEK-neat, the stiffness and strength of PEEK are improved when high concentrations of carbon fibers and nano silica are added to the matrix. However, the ductility of the PEEK/CF/nano silica composites is reduced by excessive filler loading. Higher levels of nano silica result in significantly improved friction performance. When the PV condition is increased to 1:4 and 3:2 MPa:m/s, however, a moderate number of nanofillers produces a low friction coefficient. The nanofiller content almost has no effect on the PEEK/CF/nano silica composites' friction performance under high stress. [48]

From all above list of materials given PEEK material is found to be good choice of material for the application of gear by reinforcing it with nano particles to enhance the mechanical property.

Nano-composite gear material selection

Power transmission gear performance greatly depends on the material selection. Due to the gear undergo cyclic and impact load, material designed for sever condition of automotive environment need higher mechanical property. Therefore, selection of material significant of the smooth operation of power transmission.

Several aspects are the make-up of efficient gear transmission. In the choosing of materials for gears strength is considered one of the fundamental aspects. Therefore, for this selection process material tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength, hardness etc. are used to compare material performance. From different accredited sources of research literature has been collected. The literatures show their experimental results and the data is collected the output of the experimental results. Below it is demonstrated the selection process utilized.

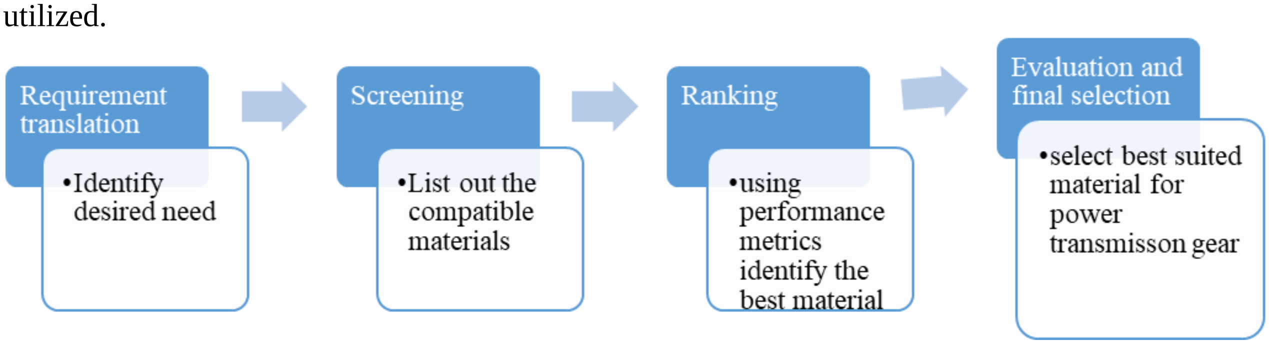


Figure 2- 4 Material selection procedure

Based on the above table, it can be seen that PEEK polymer and its nano fillers have seen to be better material properties compared to others, PEEK polymer and its nano-fillers outstand from all the listed materials. Therefore, by adding more enhancing features to the base polymer matrix PEEK, we can obtain desired material for higher power transmission gear material.

Nano-particle filler material selection for PEEK polymer matrix composite

The carbon-based nanoscale fillers are outstanding due to their ability to change a weak polymer matrix to a strong and durable high performance polymer nanocomposite and also helps in achieving exceptional mechanical properties.

MWCNTs have great tribological properties, high properties like mechanical and thermal conductivity. CNTs holds exceptional properties such as lower volume fraction of filler addition to exhibit similar property enhancement as compared to macro composite.

most literature revealed that CNTs are considered one of the best nanofiller materials because of their light weight, high mechanical strength, and excellent thermal and air stability. CNT reinforced polymer nanocomposite exhibits best quality of stiffness, strength and improved tribological properties. CNTs are also known to effectively increase thermal properties by enhancing temperature strength.

The addition of nanoparticles filler like SiO_2 in polymer materials enhances the material hardness, tensile strength, elastic modulus and more significantly thermal stability of the material. It also accounts for the betterment of ear and friction properties.

Therefore, filler material in this study MWCNT ZrO_2 and SiO_2 are selected nano filler materials to enhance the mechanical and tribological properties of Polymer Matrix Composites PEEK so as to improve its performance as a power transmission gear application. The combinations of these filler materials result remarkable improvement in the material property since one of the measurements for performance of power transmission is material property.

2.9. The use of computer program (Ansys Workbench) for nano composite analysis

There is a growing interest in the use of nanocomposite materials for a variety of applications due to their unique properties, including enhanced strength and stiffness, improved thermal performance, and reduced weight. One of the most important factors in determining the suitability of a nanocomposite material for a particular application is its ability to withstand rigorous testing conditions.

Ansys workbench software is an excellent tool for performing nanocomposite material analysis. The software is versatile and can be used to analyze a wide range of materials, including composites. The software provides detailed information on the overall structure and properties of the nanocomposite. This information can be used to help determine the suitability of a nanocomposite material for a particular application.

The accuracy and precision of the data provided by Ansys workbench software makes it an ideal tool for performing nanocomposite material analysis. Many researchers use this tool in their study for analysis. [11-13, 16, 21-23, 38, 64] The software is able to accurately identify small structural details within a nanocomposite material, which can be important when determining the suitability of a nanocomposite material for a particular application.

Overall, Ansys workbench software is an excellent tool for performing nanocomposite material analysis. The data provided by the software is accurate and precise, making it an ideal tool for determining the suitability of a nanocomposite material for a particular application.

2.10. Why is ANN better prediction tool for engineered nanocomposite materials?

Artificial intelligence methods are now being used in many fields of study for complex relations and the techniques of solving such problems are still in development. ANN are machine learning algorithms based on mathematical models that are identical and inspired by biological nerve systems, responsible for the functionality of human brain. It comprises different sets of neurons making connection to each other by axons. Artificial neurons are individual neural units that are interconnected with each other to form a network. The action of connection between individual neural units is exercised through a combination of input values and an activation function, which returns the output of a neuron.[26] The distinct feature of ANN is the instinctive creation, derivation and exploration of new information using previous learning that is called machine learning process.

2.10.1. Accuracy of ANN in comparison with experimental results

In study conducted to characterize and predict properties of polymer clay silica hybrid nanocomposite, both ANN and Regression model was used. The study shows hardness of nanocomposite increased for nanosilica from 1-2 wt% but the hardness decreased for 3 wt% compared to 1 and 2 wt% of nanosilica. The Hardness result from neural network model and regression model are compared with the experimental results with different nanofiller reinforcements. From the result maximum error is 3% for regression model and 0.036% for neural network model. Wear rate results of nanocomposites from regression model and neural network model are also compared with the experimental results for different nanofiller reinforcements as shown in Figures. It is observed that maximum errors in nanocomposites are 0.192% for neural network model and 0.193% regression model.[27]

It can be seen from the plot below that ANN model align minor or acceptable error with that of experimental results.

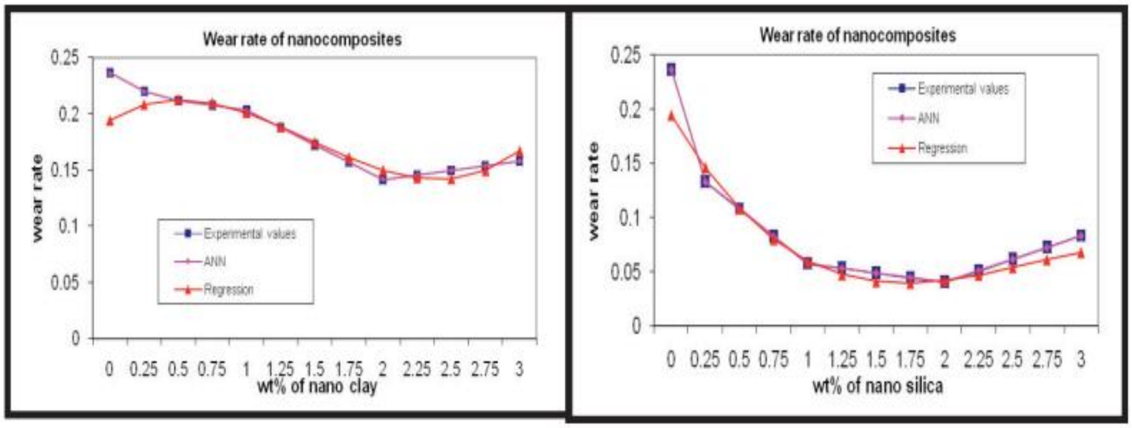


Figure 2- 5 (a) Predicted and experimental values for wear rate of clay hybrid nanocomposites, (b) Predicted and experimental values for wear rate of silica hybrid nanocomposites[27]

Comparison of predicted properties with experimental results in all the tested cases indicate that the error is less than 1% for neural network model and 5.02% in the prediction using regression model. [27]Higher error in regression model predictions is obtained since some of the factors that contribute to wear rate like condition of the applied load, track distance, travel, etc. were not taken into account. However, since neural network was trained with the experimental data and the influence of all the factors is inherently present in the data, the model is devoid of above limitations. Neural network maps the inputs to the outputs in multi-dimensions and takes care of non-linearity leading to more accurate predictions.

Experimental study for Optimization and Prediction of Mechanical and Thermal Properties of Graphene/LLDPE Nanocomposites is conducted. [29] Then the experimental values are compared with the predicted values from ANN for thermal conductivity of CGNPs/LLDPE composites prior experimental test. From the result it is observed that predicted values and experimental values were very close to each other. For training the network, Levenberg-Marquardt algorithm was used. The sum of mean square error (MSE) for the training and test data indicates the accuracy of the ANN predictions. The selection of 5 hidden neurons achieved the lowest MSE and a high correlation coefficient.

The average relative error in predicting the tensile strength of nanocomposites by the developed neural network model is found to be very low (0.0396), indicating that predicted results matched the experimental results. The results in this study proved the ability of artificial neural network to predict the complex relationship between screw (and feeder) speed and wt% of GNPs filler and the resulting thermal conductivity, crystallization temperature, degradation temperature, and tensile strength of the composite materials. [32] The mean relative error is very low, that is, 0.0258%, between the experimental data and neural network prediction, which implies a good agreement between simulation and experimental results.

2.10.2. Material property prediction in engineered materials

Artificial neural networks (ANNs) are used to model the functional relationship between the tribological properties of polycarbonate composites and selected parameters, particularly testing conditions and material composition, in order to examine the wear behavior of polycarbonate-based composites filled with Graphene and Boron carbide particles and used as bearings, bushings, slides, and gears. The neural network was trained and tested using a total of 120 independent wear measurements from a sliding test with diverse wear testing settings and material composition. For the purpose of improving the quality of prediction, 90 datasets from the database were randomly selected as training datasets, and the remaining 30 datasets were utilized to test the ANN. The database contains input parameters as (a) material composition involving volume fraction of Graphene, Boron carbide particle and polycarbonate, (b) testing conditions involving sliding speed and applied load. [30] Output parameter involves wear characteristics such as friction coefficient and wear. Compared to experimental results, the prediction quality converges to experimental value.

Using ANN, an attempt is made to determine how the applied load, experimental period, and SiC weight percent affect the wear behavior of aluminum matrix composites gear that contains varying weight percents of SiC microparticles (5% and 10%) and nanoparticles (1% and 2%). The Levenberg-Marquardt algorithm was used to verify the data and make outcome predictions. The model had one hidden layer with 10 neurons, one output layer with one neuron, and one output that was fixed for the wear percentage. The three input parameters were applied load, experiment time, and Si Cwt%. Also evaluated were the experimental and projected wear percentages. The findings indicate that there is no discernible difference between the experimental and projected values. For the micro and nanocomposite, the highest computed errors were determined to be 6.46% and 7.61, respectively. [31] The obtained error is acceptable and shows that the ANN model predicted wear with reasonable accuracy. Thus, the results of the confirmation test showed the successful generation of the prediction mode.

An integrated ANN and Genetic Algorithm (GA) approach is employed in a different study to model and optimize surface roughness when milling PA-6/NC nanocomposites. The statistical output results show that the method may be effectively employed for precise relationship modeling during milling of PA-6/NC nanocomposites. Using training and testing data, it was discovered that the mean absolute percentage errors were 2.99% and 2.49%, respectively. [28] These findings show that the constructed model can predict surface roughness within the parameters of the machining settings examined in the study with a high degree of accuracy, leading to the conclusion that ANNs can be employed for surface roughness analysis and optimization.

Therefore, ANN is a highly suitable tool for predicting mechanical and tribological properties and can be used with reasonable confidence for predicting the behavior of synthetic materials even before they are actually manufactured, thus saving considerable time, effort and money.

2.10.3. Prediction of material composition in composite material

To attain the desired filler content for cotton fiber/polypropylene composite while satisfying the desired targeted qualities, an artificial neural network model has been designed. To build a relationship between the mechanical properties, previously collected experimental data sets were trained on the TensorFlow backend using the Keras package in Python. The fundamental difficulty is that the relationship between the mechanical properties under consideration is nonlinear. Therefore, because of this complicated relationship and the paucity of data, determining the ideal filler content based on mechanical qualities may be difficult. Higher neuron counts with fewer data points can occasionally cause the model to fit too well or too poorly.

To test the model's dependability, the ANN model was run at least five times for each prediction. Additionally, the intended mechanical qualities were purposefully changed to see if the model was fixed (due to over fitting) to any particular solution or if it could be made more flexible by changing the independent variable. The experimental investigation provided the essential experimental data for input. In order to develop an effective co-relation between the eight feature independent inputs (i.e., net fiber weight, initiation energy, propagation energy, total energy, ductility index, tensile strength, modulus elasticity, and elongation) and one dependent out, which is the ideal value of the predicted ideal filler content, it was discovered that four hidden layers with 200 neurons each were required. [33, 34] The developed approach proved to be very efficient and reduced the time and effort of the material characterization.

During literature survey, research gaps found out are addressed in the following points.

- Computation of composite material properties using mathematical formula from the constituent properties is very complicated; thus, researchers use experimental investigation; whereas recently discovered artificial neural network (ANN) method is one way to predict material properties which is cost and time effective for discovery of new materials. Artificial neural network (ANN) method is capable of computing with complex input and output variables like that of composite materials with great accuracy. But not enough application of artificial neural network (ANN) method is implemented in researches which motivates researchers for discovery of advanced materials.
- Literature revealed that numerous research studies have been reported since last century for alternative gear materials. But the application of composite material is limited in automotive component particularly in engine environment. By conducting study on tribological behavior analysis in tis extreme condition, alternate material development and application of those material will enable full exploitation of composite materials. As a result, the application of enhanced composite material will decrease weight and fuel consumption of the vehicle, because most vehicle weight is in the engine and power transmission component, which results in the development of light and green technology.

Chapter 3: Material and Method

To obtain enhanced material for the application of gear, there are different steps and procedures to be employed. The first step is to identify suitable material with higher performance for the application gear. These materials will be compared and outstanding material will be selected with unique material composition. The newly developed material property is then predicted by using machine leaning method or artificial neural network (ANN) method. Then finite element method (FEM) analysis will be conducted to check the material loading capacity, strength, contact stress fatigue life cycle and factor of safety of the gear using Ansys Workbench. For this research the methodology followed in order to meet the research main objective is laid out in process flow diagram as shown below.

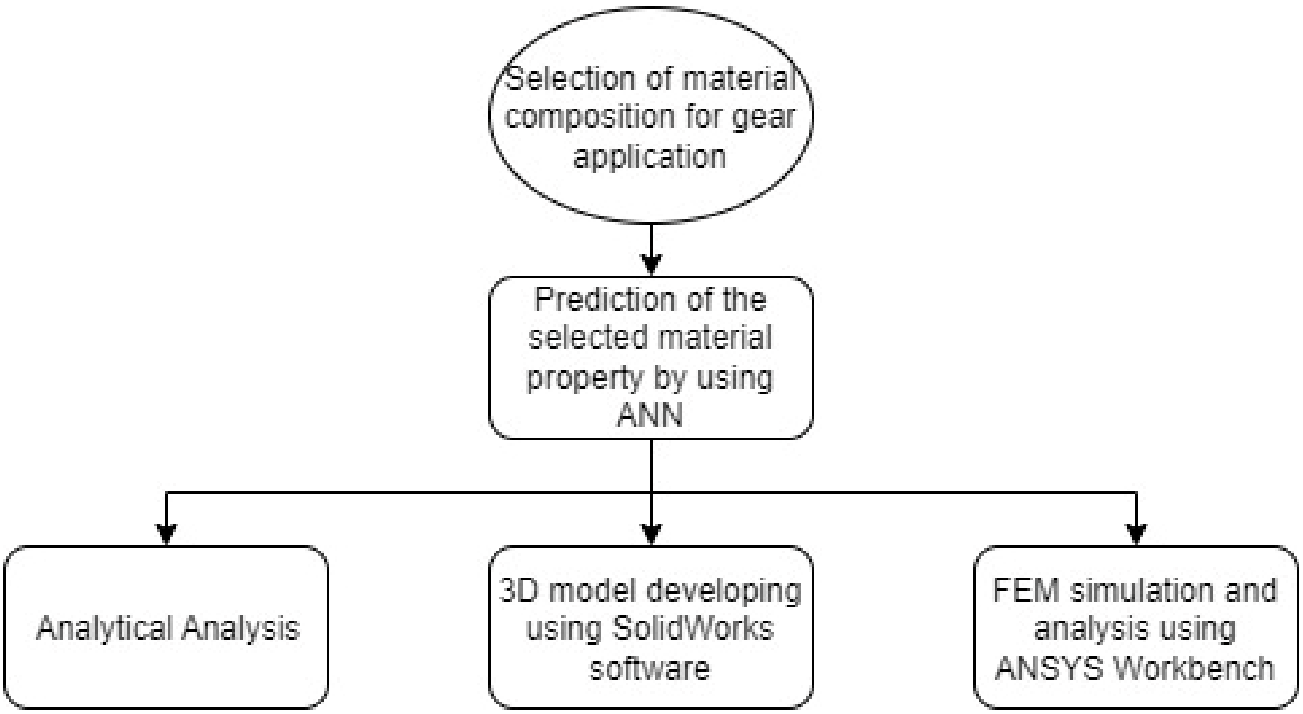


Figure 3- 1 Methodology of the research

Material Selected

Gear material that is used for the research is PEEK polymer matrix composite material and the nano filler multi-walled carbon nano tube (MWCNT), Zicronia (ZrO_2) and Silica (SiO_2) are selected as it has been briefly discussed in the literature review section. The exact composition of the material should be determined by modeling machine learning algorism in order to predicting the material property by feeding data in to MATLAB machine learning model. For the prediction different sets of concept material datasets are prepared by answering the question what is the best possible combination of nano particle fillers to obtain enhanced material and by selecting optimum amount of filler composition gathered from different sources of literatures. By varying material composition concept materials are listed as it is tabulated in the Appendix A:1.

Table 3- 1 PEEK Polymer matrix material Data

No.	Material property	Units	Value
1.	Density	gcm^{-3}	1.32
2.	Tensile strength	MPa	95
3.	Tensile elongation	%	58.4
4.	Tensile modulus	GPa	3.72
5.	Flexural strength	MPa	141
6.	Flexural modulus	GPa	3.5
7.	Compressive strength	MPa	170
8.	Impact strength	KJm^{-2}	5.0
9.	Shore D hardness		85
10	Melting point	^oC	343
11	Glass transition temperature (Tg)	^oC	143
12	Thermal expansion coefficient	ppm $^oC^{-1}$	45
13	Thermal conductivity	W m^{-1} ^{o-1}C	0.87

3.1. MATLAB Machine Learning Modeling and training

The first step in creating an ANN model is gathering data from various sources. This data is then filtered in order to remove any incorrect or irrelevant information. The data input and output are efined and collected next in excel file. Last but not least, the data is moved from Excel files to MATLAB files. The ANN model is then selected, and its architecture is established. The training algorithms are chosen, and the training functions are produced after that. The ANN model is lastly trained using the cleaned data. After training, the trained ANN is used for simulation and prediction, and the performance of the ANN model is assessed.

Data collection

Datasets that are required to connect the input and output variables of the models serve as the foundation for the construction of machine learning models. The dataset's size and quality affect the precision and effectiveness of the machine learning models.

Dataset Analyzing

In general, there are inconsistent data in the dataset formed by collecting test data from different sources. This process identifies and remove irrelevant data for this study from the dataset.

Dataset Normalization

The raw data extracted from literature often have different units and scales of magnitude. Thus, normalization of the data is performed in order to keep the uniformity of the data.

The dataset used to train, test, and validate the ANN modeling was collected from various experimental test results related to transmission gear materials that were published in [50- 75].

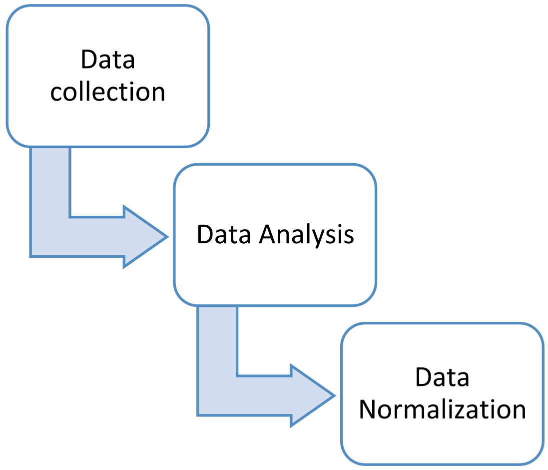


Figure 3- 2 Material data refining process for Machine learning process

Appendix A:1 of the appendix is a table of the gathered data. Data for training, testing, and validating are then separated out into three categories. Out of the total amount of data gathered, 70% are chosen as training data, while the remaining 30% are made up of testing data and validating data (15% each). The training, testing, and validating dataset's structure has been built up as input parameters represented in material composition. The dataset's output parameter is also expressed in terms of mechanical properties.

Epoch refers to training and testing done with the ANN. The instances in the training set are used to change the connection weights of the neural network at each epoch, and the dataset is randomized. The number of nodes in the input layer, the number of hidden layers and the number of neurons in each hidden layer, and the large number of neurons in the output layer are all considered to constitute the neural network architecture. The input, hidden, and output layers make up at least three of the layers that make up the ANN's architecture. A multilayer feed-forward neural network has been used in this investigation.

Identification of input and output parameters for ANN material property prediction

The connection between individual neurons, which can be either reinforcing or inhibitory, is the fundamental component of artificial neural networks. An activation function that returns the output of a neuron is used in conjunction with input values to exert this action. The autonomous production, derivation, and exploration of new material using prior learning—known as the training process—is another unique aspect of ANNs. [76]

The strength and stiffness of the printed gears on spur gears made from pure acrylonitrile butadiene styrene and nano clay bound nanocomposite were investigated in the literature [77]. The outcome demonstrates that the addition of nanoparticles to the polymer causes relative variance. In comparison to pure acrylonitrile butadiene styrene and nano clay-bonded gear materials with varying weight percentage increments of nano clay, the material's hardness, tensile strength, modulus of elasticity, and tensile elongation are influenced or modified.

Many literatures show that changing the weight or volume percentage of composition of nano fillers results in significant change in material property.

Literatures [78-81] commonly used chemical composition of the nanocomposite as an input and material properties for the output in applying ANN to train the predictive model of material properties. Hence it can be seen that these parameters greatly contribute for the prediction model.

The property that co-relates the composition of weight percentage of nano filler has vital role.

Therefore, the training input parameters includes chemical composition of nanocomposite material and the target or output parameters are tensile strength, modulus of elasticity, Melting Temperature, density and tensile elongation.

The selection for the input parameters and output parameters to train ANN model is selected based on the above justification

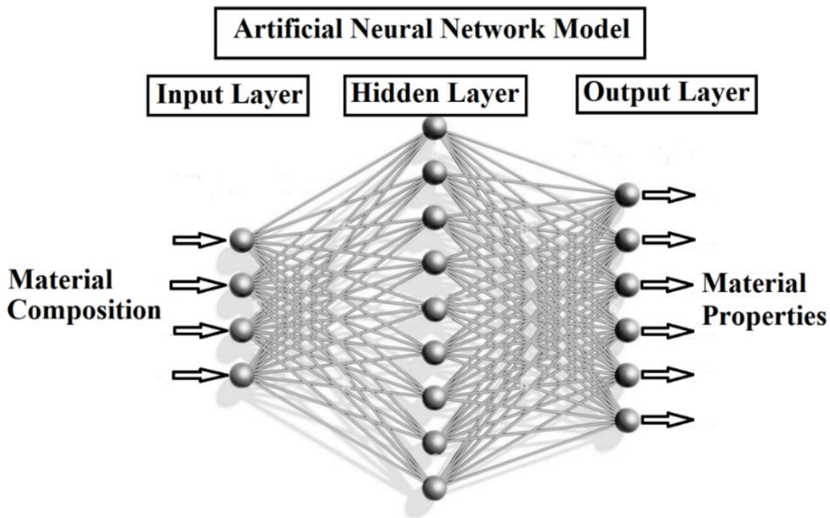


Figure 3- 3 MATLAB Neural Network Model

In the diagram above, the ANN has input parameters like the composition of the material, and the output outcomes are tensile strength, modulus of elasticity, Melting Temperature, density and tensile elongation. The input and output parameters utilized to predict the mechanical properties of nanocomposite reinforced PEEK material are shown in the table below. The database has mechanical properties of composite materials as output parameters and material composition as input values (tensile strength, modulus of elasticity, Melting Temperature, density and tensile elongation).

Table 3- 2 Input and Output parameters for ANN

The input and output parameters for Artificial Neural Network Model	
Input	➢ Material Composition
Output	➢ Tensile Strength ➢ Tensile Modulus ➢ Flexural Strength ➢ Flexural Modulus ➢ Melting Temperature ➢ Density ➢ Percent Elongation

Steps and procedure for creation of MATLAB

The following procedures were used in prediction of the material properties of the new input.

1) Start MATLAB and Import inputs and targets from experimental data (Appendix A:1)
2) Open the artificial neural network toolbox
3) Create the MATLAB code.

During creation of the network code, the following parameters was considered for this work.

a) Feed-forward back propagation type of network was selected among the available network types. This is due to the effectiveness and relative ease of this type of network compared to the other.
b) Choose training function.

The chosen network training function employs gradient descent to adaptively update weight values. In this work trainlm training function is used, because it is usually fastest.

c) Choose training algorism

Levenberg-Marquardt, Bayesian regularization, and scaled conjugate gradient are the three training algorithms. Usually, the Levenberg-Marquardt algorithm uses more memory but takes less time. Levenberg-Marquardt type is employed in this study.

d) Choose number of hidden layers and number of neurons.

One hidden layer was chosen as it has proven to be sufficient in many cases.

4) Create the network: the network was created with 20 input, 20 hidden and 7 output neurons

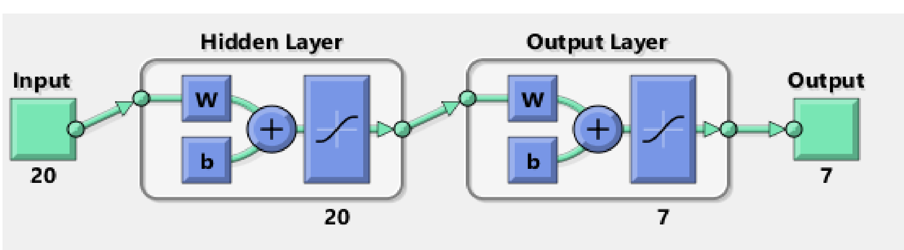


Figure 3- 4 ANN model structure

5) Training the Neural Network: -

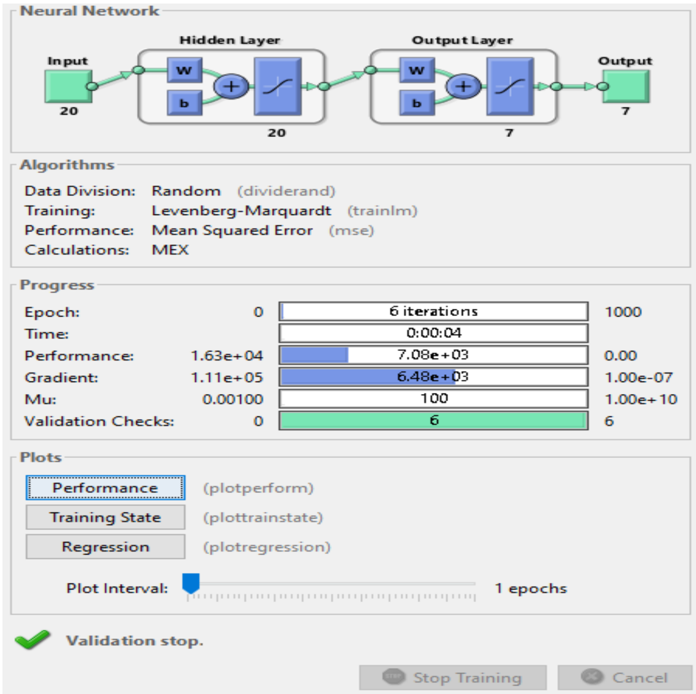


Figure 3- 5 Training process of ANN

This is the basic portion of the prediction work since the outcome (prediction) in comparison to true value is evaluated from many angles. The network was trained using the input and output data from the data given in Appendix A:1. After the initial trained network is complete, performance metrics are used to cross-check the output (Regression fit).

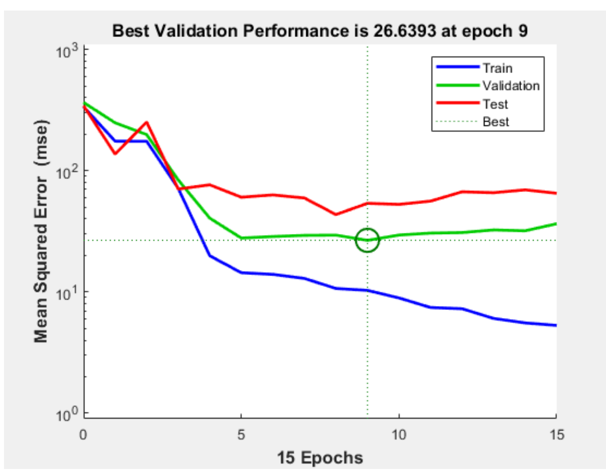


Figure 3- 6 Validation Performance graph

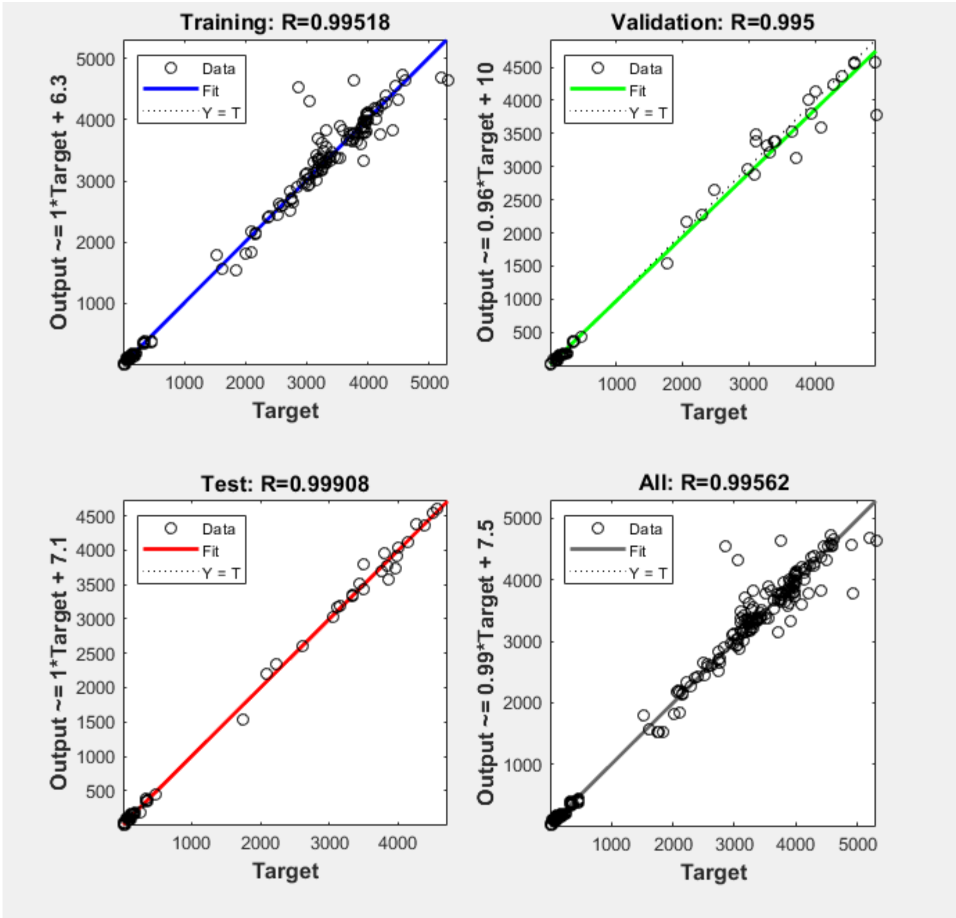


Figure 3- 7 Performance of Training, Testing and Validation

6) Simulate the Trained Network

The trained network was simulated to achieve the necessary anticipated material property with regard to the new material input in the table above after achieving the best performance from performance measurements.

This was accomplished by creating a database of 78 experimental tests, of which 50 records were used for training and 28 for testing and validation (chosen randomly).

Given the complex relationship between the material composition and material property the proposed ANN model has a potential alternative approach to traditional statistical methods.

In order to forecast the material properties, an artificial neural network model can be utilized rather than expensive, challenging experiments that call for specialized equipment, training, and knowledge. This technology can be used by researchers to predict material properties and create and develop new materials with ease.

3.2. Analytical Method of analysis

Based on different assessment and consideration gear specification is tabulated below in table 7.

Table 3- 3 Spur Gear Tooth Profile Parameters

Center distance	96 mm
Module	2
Driving and Driven gear tooth number	48
Gear Diameter	96 mm
Pressure angle	20º
Face width	18 mm
Applied Torque	25 Nm
Running speed	1,450 rpm

3.2.1. Gear tooth Bending Analysis

One of the crucial elements considered in the analysis of spur gears is the bending stress. The gear tooth will probably fail in bending if the total repetitive load acting on it exceeds its strength. Wiltred Lewis created a formula that predicts gear bending failure. As illustrated in Figure, the tangential load (Ft) causes bending stress, which has the tendency to break the tooth. The formula uses the bending of a cantilever beam to model the bending stress acting on the gear.

Maximum bending stress brought by the tangential force is given by

$$\sigma_b = \frac{MC}{I} = \frac{F_t l\, C}{I}$$ *Equation 1*

Where M = Maximum bending moment= $F_t l$

F_t = Tangential load acting at the tooth

l = Length of the tooth

C = Half of thickness of the tooth $(t) = t/2$

I = Moment inertia = $bt^3/12$

b = Face Width of gear

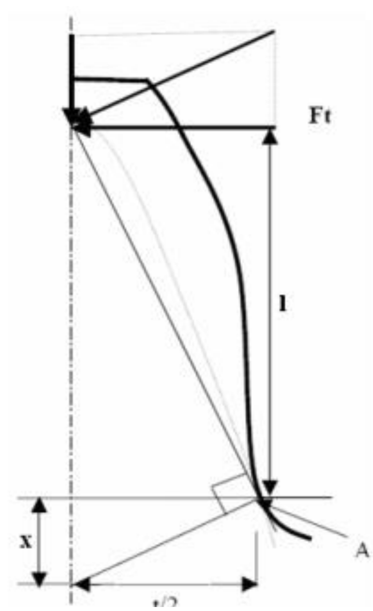


Figure 3- 8 Partial view of Spur gear load application

Substituting the values for $M, C \text{ and } I$ in Equation 1 the stress will be modified to:

$$\sigma_b = \frac{6F_t l}{bt^3} \qquad \text{Equation 2}$$

From the figure, the similarity of the two triangles which is shown in Figure 15,

$$\frac{t/2}{x} = \frac{l}{t/2} \Rightarrow l = t^2/4x \qquad \text{Equation 3}$$

Substituting equation 3 into equation 2 and then multiplying by a term P_d/P_d, it becomes

$$\sigma_b = \frac{3F_t}{2bx} = \frac{3F_t P_d}{2P_d bx} = \frac{F_t P_d}{bY} \qquad \text{Equation 4}$$

Where, P_d = diametral pitch

$$Y = \frac{2}{3} x P_d \qquad \text{Equation 5}$$

Equation 4 is known as Lewis equation, which considers only static loading and doesn't take the dynamics of meshing teeth into account. The above stress formula must be modified to account different situations like stress concentration and geometry of the tooth. Therefore, Equation 5 that is shown below is the modified Lewis equation recommended by AGMA for practical gear design to account for variety of conditions that can be encountered in service.

$$\sigma_b = \frac{F_t}{m_n bJ} \frac{K_a K_m}{K_v} K_s K_B K_I \qquad \text{Equation 6}$$

Where K_a = Application factor = 1.5
K_v = Velocity factor = 1.3
K_m =Load distribution factor = 1.6
K_s = Size factor = 1 unless teeth are very large
K_B = to account for gear with a rim and spokes = 1 for solid gears
K_I = to account for extra loading on idler
K_I =1 for non-idler gear, K_I =1.42 for idler gears
J = Geometry factor = 0.30
Ft = Tangential load
m_n = Normal module = 2 mm

This analysis considered only the component of the tangential force acting on the tooth and doesn't consider the effects of the radial force, which will cause in compressive stress over the cross section on the root of the tooth. Suppose that the greatest stress occurs where the force is exerted at the top of the tooth, usually there are at least two pairs in contact. In fact, the minimum stress at the root of the tooth occurs when the contact point moves near the pitch circle because there is only one tooth pair in contact and these teeth pairs carries the entire torque or load. When the load is moving at the top of the tooth, two teeth pairs share the whole load if the ratio is longer than one and less than two.

the modified Lewis equation becomes: $\sigma_b = \frac{F_t}{m_n bJ}\frac{K_a K_m}{K_v} K_s K_B K_I$ *Equation 7*

$$\text{Where, } F_t = \frac{T}{R\cos\varphi} = \frac{21\ Nm}{0.048\ \text{m}\cos 20^0} = 465.58\ N$$

$$\sigma_b = \frac{F_t}{m_n bJ}\frac{K_a K_x K_m}{K_v} = \frac{465.58\ N}{2x10^{-3}\ x\ 0.018m\ x\ 0.30}\frac{1.5\ x\ 1.6}{1.3}\ x\ 1$$

$$\sigma_b = 79.586\ MPa$$

If two tooth pair is considered to carry the whole load and it acts on the top of the tooth, this loading condition is enough to analyze the gear bending stress.

3.2.2. Contact analysis

Contact mechanics is the study of how solids that are in contact at one or more locations deform. The area of contact between two gears is, in theory, a line. As the gear tooth surfaces roll and slide during operation, the curvatures of the individual mating surfaces at the points of contact will change depending on the specified tooth profile dimensions of the matching gears as well as the instantaneous positions of the point of contact on the line of action. Therefore, the nature of contact is comparable to that of two contacting cylinders with continuously varying curvature radii.

Although it is a line contact in theory, due to mutual compressive pressure, the line actually develops into a band throughout the length of the teeth. The center of the point of contact experiences the highest compressive stress when the gear tooth surfaces are operating.

Modeling contact problem using parallel cylinders in contact

It is common to disregard this and treat the contact of spur gear teeth as similar to the contact of parallel cylinders with the same radius of curvature at the point of contact because the radius of an involute gear tooth will vary significantly across the width of contact with a mating tooth. Therefore, spur gears can be modeled using the Hertzian equations. The gear teeth are regarded by Hertz theory as an analogous contacting cylinder, as indicated in the Figure 16.

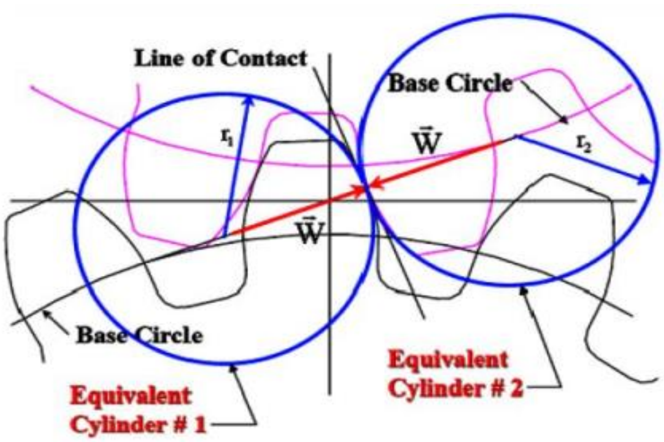


Figure 3- 9 Cylindrical contact between two spur gear

Hertz Theory of Contact

A contact area and a pressure distribution over this area are created when two surfaces come into contact. The contact theory of Hertz (1881) can be utilized to determine the contact area and pressure distribution if the surfaces have a straightforward geometry. The curvature of the contacting bodies determines the geometry of the contact region. The simplified contact of two parallel cylinders is shown below in the Figure 17 based on the Hertz theory to demonstrate the contact between two elastic bodies.

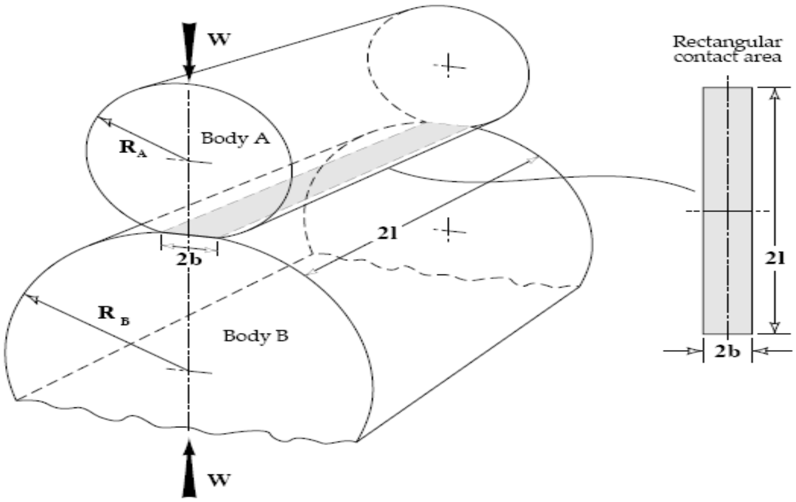


Figure 3- 10 Hertzian Cylindrical contact model

Typically, a frame of reference is established in which the objects—which may be in motion relative to one another—are static in order to streamline the solution process. At their interface, they communicate through surface tractions (or pressures/stresses). When figuring out the answers to Hertzian contact problems, the following presumptions are made:

- The strains are small and within the elastic limit.
- The surfaces are continuous and non-conforming (implying that the area of contact is much smaller than the characteristic dimensions of the contacting bodies).
- Each body can be considered an elastic half-space.
- The surfaces are frictionless.

From the figure above, the width of the contact zone is 2B. then the total contact force and contact pressure is, given by the formula illustrated below [2], which shows the association between the force and the pressure x

$$P_{max} = 2F\pi BL \quad \textit{Equation 8}$$

Contact width, $$B = \sqrt{\frac{4F}{\pi L} x \frac{\left(\frac{1-v_1^2}{E_1}\right)+\left(\frac{1-v_2^2}{E_2}\right)}{\frac{1}{R_1}+\frac{1}{R_2}}} \quad \textit{Equation 9}$$

B - Contact width

F - Normal load

L - Length of contacting cylinders

v_1, E_1 - Elastic properties of cylinder 1

v_2, E_2 - Elastic properties of cylinder 2

R_1, R_2- diameters of cylinders 1&2 respectively

Half of the contact width can be written as $B = \sqrt{\frac{4FR_e}{\pi L E_e}}$ *Equation 10*

Where R_e is equivalent radius of curvature given by $R_e = \frac{1}{R_1} + \frac{1}{R_2}$

R_1 and R_2 the instantaneous value of the radius of curvature on the gear tooth profile

At the pitch point R1= Rp & R2= Rg and given by

$$R_p = d_p \sin\varphi/2$$

$$R_g = d_g \sin\varphi/2$$

Where dp & dg are the pitch diameters, for Pinion and gear respectively and φ is the pressure angle. Therefore, at the pitch point Re becomes

$$R_e = \frac{1}{\frac{1}{R_p}+\frac{1}{R_g}} = \frac{1}{\left(\frac{2}{\sin\varphi}\right)\left(\frac{1}{d_p}+\frac{1}{d_g}\right)}$$ *Equation 11*

Where the radius of the gear and the pinion is equivalent which is 48 mm and the pressure angle is $\varphi = 20^0$

Therefore, $R_e = \frac{1}{\left(\frac{2}{\sin\varphi}\right)\left(\frac{1}{d_p}+\frac{1}{d_g}\right)} = \frac{1}{\left(\frac{2}{\sin 20^0}\right)\left(\frac{2}{0.048\ m}\right)} = 4.104x10^{-3}\ m$

And Ee is the equivalent modulus of the material, given by

$$E_e = \frac{1}{\left(\frac{1-v_1^2}{E_1}\right) + \left(\frac{1-v_2^2}{E_2}\right)}$$

Where the gear poisons ratio and modulus of elasticity is determined by prediction of material property. Since we are applying the same material for pinion and gear the material property for both gears are the same; i.e. $v_1 = v_2 = 0.3$ and $E_1 = E_2 = 3.66\ GPa$

Therefore, $E_e = \frac{1}{\left(\frac{1-v_1^2}{E_1}\right)+\left(\frac{1-v_2^2}{E_2}\right)} = 2.01\ GPa$

Substitute the value of B from the above equation, to find the maximum contact pressure.

The maximum contact stress is given by:

$$P_{max} = \sqrt{\frac{FE_e}{\pi L R_e}} \qquad \textit{Equation 12}$$

For the driver pinion, and gear follower, $F = F_N = \frac{F_T}{\cos\varphi} = \frac{T_p}{R_p \cos\varphi} = \frac{21\ Nm}{0.048\ \mathrm{m}\cos 20^0} = 465.58\ N$

$$P_{max} = \sqrt{\frac{T_p E_e}{\pi L R_e\, R_p \cos\varphi}} \qquad \textit{Equation 13}$$

Where
- R_p radius of the pinion gear
- T_p Applied torque on the gear
- F_N Normal force on the gear
- F_T Tangential component of the force on the gear

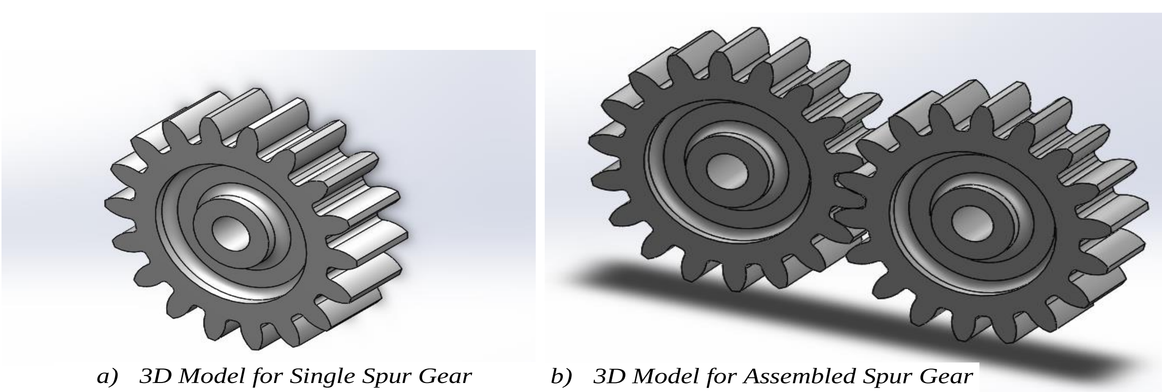
Finally, the maximum pressure on the gear is $P_{max} = \sqrt{\frac{T_p E_e}{\pi L R_e\, R_p \cos\varphi}} = \sqrt{\frac{21\ Nm\ x\ 2.01\ GPa}{\pi x 0.018\ m\ x\ 4.104x10^{-3}\ m\ x\ 0.048\ m\ x\ \cos 20^0}} = 63.5\ MPa$

3.3. FEM ANALYSIS AND CONDITIONS

Polymer Nanocomposite Spur Gear CAD 3D model generation

Using the commercial software SOLIDWORKS, 3D model of spur gear is created by applying the general procedure to create tooth profile of spur gear. To create or model the tooth profile the listed parameters in the table are used to create the tooth profile of spur gear using CAD software Solidworks.

In order to simulate the FEM dynamic analysis of polymer nanocomposite spur gear, the 3D model should be generated. Therefore, the 3D model spur gear created using the commercial software Solidworks can be seen in the figure 18.



a) 3D Model for Single Spur Gear *b) 3D Model for Assembled Spur Gear*

Figure 3- 11 3D Model for Spur Gear

3.3.1. Defining Material Properties

The following step is to insert the gear material's Young's modulus, Poisson's ratio, and density, which were used in the previous chapter's analytical computation. This can be done by selecting the Engineering Data from the analysis tab of the ANSYS Workbench and inserting the corresponding values. The materials that were used for analytical determination of stress has been added to the engineering data and used for the stress evaluation in ANSYS workbench.

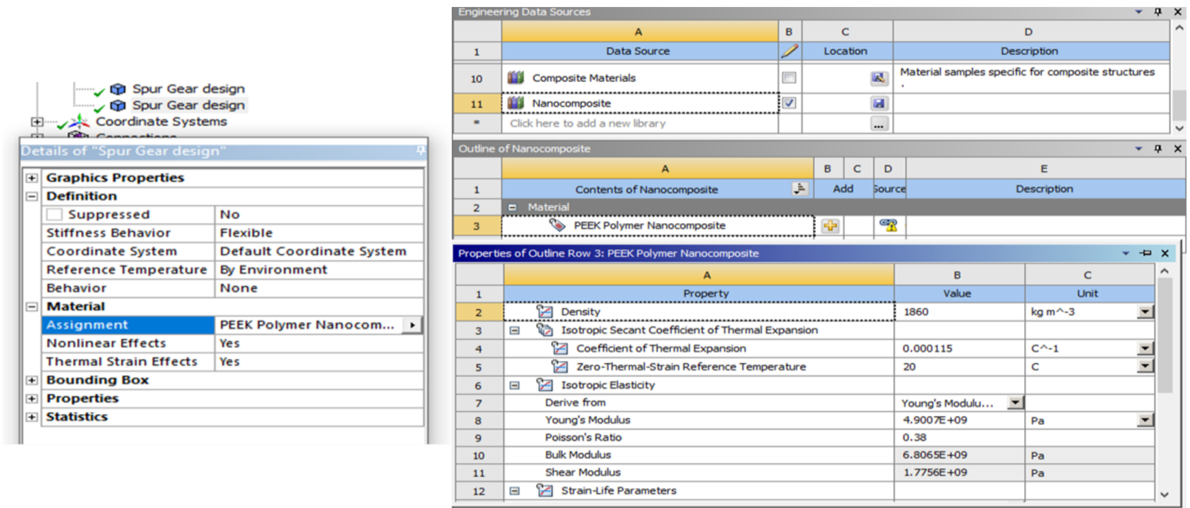
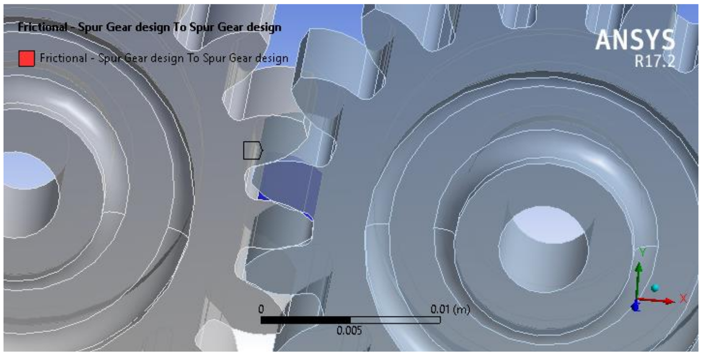


Figure 3- 12 Defining material property in ANSYS workbench

3.3.2. Defining Contact Region and Coefficient of Friction

The next step is to specify the contact between the two involutes teeth once the geometry has been added to the Static Structural Analysis tab. An integrated feature of ANSYS reads the attached geometry for any predefined contacts or other boundary definitions automatically. Frictional contact is required between the two teeth; the illustration below illustrates what is meant by this. Change the Interface Treatment to "Adjust to touch" as one of the most crucial steps. The type of contact between the selected bodies is specified by this option. The image from ANSYS that depicts the contact defined for the two spur gear teeth in mesh is shown in the figure below. Simulation will be done for Lubricated Condition.



Details of "Frictional - Spur Gear design To Spur Gear ...

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	Spur Gear design
Target Bodies	Spur Gear design
Definition	
Type	Frictional
Friction Coefficient	0.3
Scope Mode	Manual
Behavior	Asymmetric
Trim Contact	Program Controlled
Suppressed	No
Advanced	
Formulation	Augmented Lagrange
Detection Method	Nodal-Normal From Con...
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled

Figure 3- 13 Defining contact region and coefficient of friction

3.3.3. Mesh Generation

The mesh with the default settings is not adequate to get the accurate results. In this analysis both the gear was finely meshed with "Sizing" option in menu. The element size was chosen to be 0.01. Additionally, contact sizing is used in order to observe the effect in the contacting region The image below shows the meshed assembly.

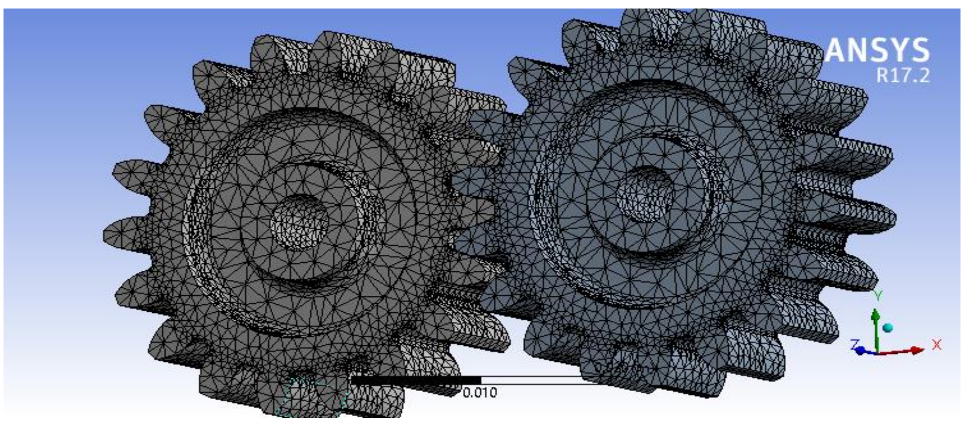


Figure 3- 14 Mesh generation

3.3.4. Supports And Loads

The lower gear is given a fixed support and the top gear is given frictionless support. The top gear is also given a toque or a moment in clockwise direction. The image below shows how the supports and loads were applied to the gear model.

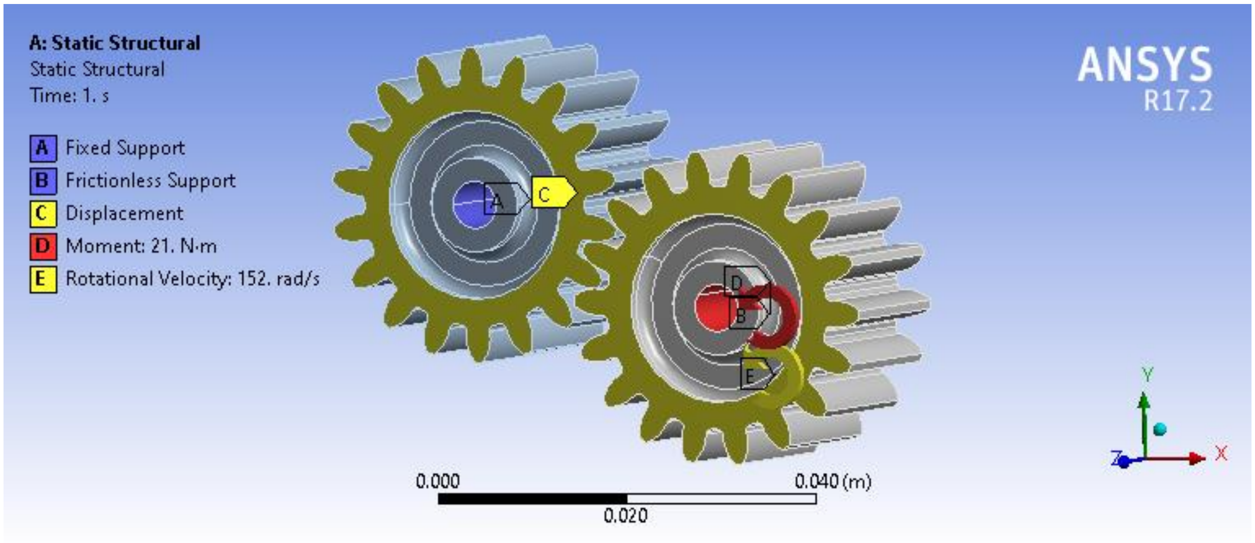


Figure 3- 15 Defining Support and Load for the gear

3.3.5. Defining the Result

Ansys has the contact tool and fatigue tool which we can simulate the wear and fatigue damage as well as the running cycle of life of the gear.

3.4. Preparation of MWCNT, SiO_2 ZrO_2 nano particle reinforced PEEK for gear material application

Multiwall carbon nanotubes (MWCNTs), nano-silica (SiO_2), and nano-Zirconia (ZrO_2) are the nanofillers selected, as they can react with the PEEK polymer to contribute a significant improvement to the polymer cross-linking web and bonding.

Manufacturing the prepared nanocomposites is recommended, which were composed of above-mentioned materials by melt-mixing method. It is reported that mechanical property of the nanocomposites improved by using this method of manufacturing. [42] In addition, the manufacturing method revealed the uniform dispersion of the nano particles in polymer PEEK matrix. Therefore, this method is suggested that melt-mixing can be a useful method to improve the mechanical properties of nanocomposite PEEK polymer matrix.

The mechanical alloying cyclic operation mode should be selected to the optimum time and rotary speed of mixer in order to allow modification of the process kinetics to avoid sticking and agglomeration in the manufacturing process.

Agglomeration is when particles are combined loosely which can be simply be avoided by varying the mechanical forces. Using optimal parameters of in the manufacturing machine can lead to an effective breaking of aggregates making it more dispersed nano fillers in the polymer composite.

Roughness

Because it causes unneeded increased friction, surface polish of a material is fundamental for the performance of the material in moving parts. The material's surface finish should be taken into consideration during manufacture. The term "surface finish" typically refers to the degree of polishing or texture desired for the surface of the item or component.

The desired finish of a job depends on the product application, material, and type of finish your part requires. And since we are using the material for gear application which the coefficient of the friction needed to be lower.

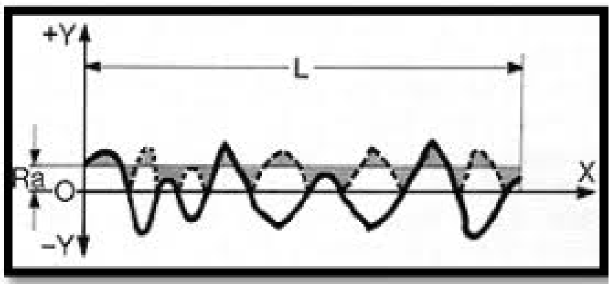


Figure 3- 16 Surface Roughness: Ra

Surface texture, also known as surface roughness, is determined by employing a single numerical parameter, Ra, to calculate the relative roughness of a surface profile. Just take the height of all of the tiny peaks and valleys.

Chapter 4: Results and Discussion

4.1. Predicted material and material property from ANN prediction

The simulated output using new input were the predicted mechanical properties that we want to develop. ANN has been used to identify the interrelation of input variables and output variables. Output variable are predicted consisting of the material five unique mechanical properties. The predicted material mechanical properties for the PEEK polymer matrix composite material and the nano filler multi-walled carbon nano tube (MWCNT), Zicronia (ZrO_2) and Silica (SiO_2) are presented in the table below.

Table 4- 1 Predicted material and material property

Material Composition / Material Property	Material			
	polymer	Nano particle filler		
	88% **PEEK**	4% **MWCNT**	5% **SiO_2**	3% **ZrO_2**
Tensile strength	**107.40 MPa**			
Tensile Modulus	**3660.62 MPa**			
Flexural strength	**159.88 MPa**			
Flexural Modulus	**4900.65 MPa**			
Density	**1.86 g/cm^3**			
% Elongation	**20.65**			
T^o melting	**375.64 ^{o}C**			

Comparing the predicted material property with recently developed gear material

The predicted material property of nano composite PEEK gear was compared with that of recently developed gear material. The results shows that the predicted material property which is nano particle reinforced composite PEEK gear is superior to that of recently developed similar groups of gear material in all the tested properties.

Material property of other nanocomposite gears that are engineered by optimizing their property is shown for comparison with the predicted material property obtained in this study.

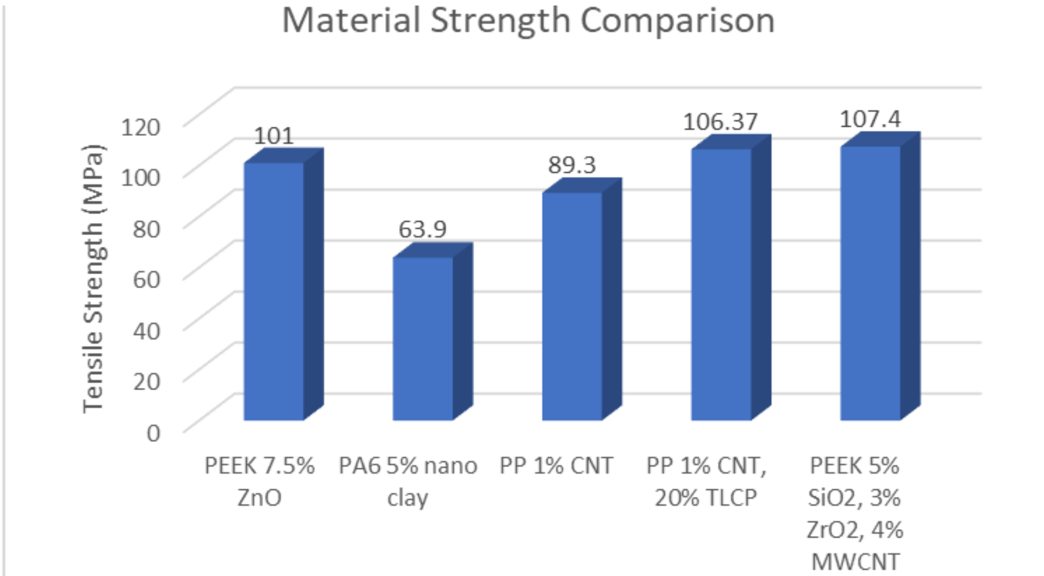


Figure 4- 1 Comparison material property of the recently developed nanocomposites materials

The predicted material property for the new gear material is much stronger than the currently used gear material. The new gear material is also more durable, which will allow for longer periods of use without needing to be replaced.

4.2. Static Analysis in ANSYS Results

4.2.1. Bending Strength Analysis

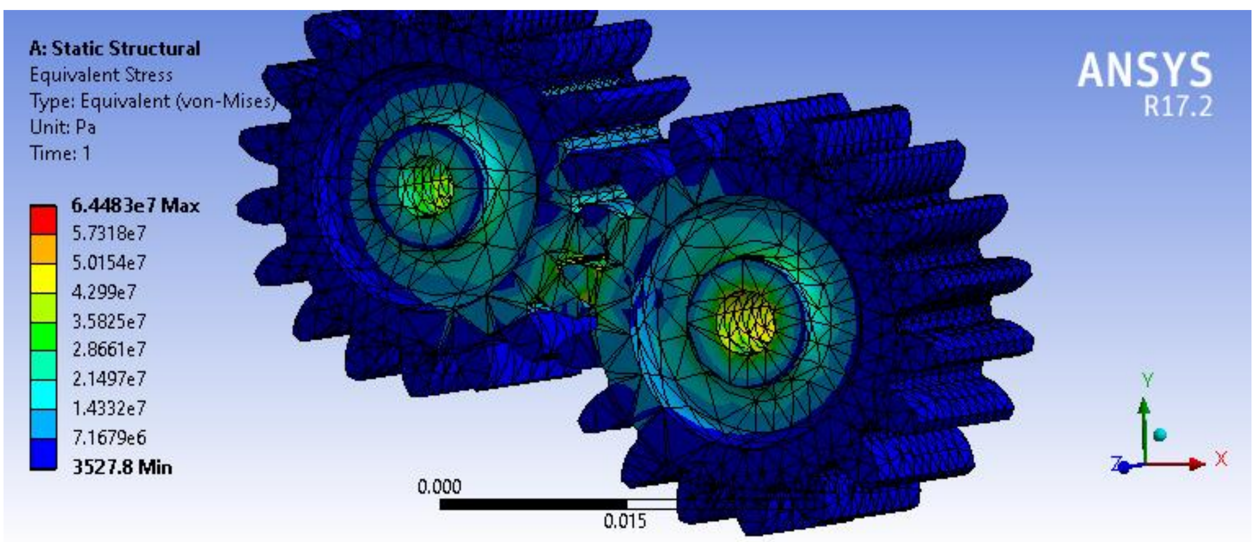


Figure 4- 2 Static Structural: Equivalent (Von Mises) stress Ansys result

The Equivalent stress

The equivalent stress or von-mises stress at the tooth root can be considered bending stress because at the root of the teeth due to the transmitted load bending effect. The bending stress is calculated using a cross section of face width by tooth thickness and the assumption that the gear tooth is a cantilevered beam. Spur gear tooth load and bending stress are directly correlated.

Bending failure often happens when the tension on the tooth is greater than or equal to the yield strength of the material used to make the gear tooth.

Maximum bending stress that was created during gear meshing at a crucial gear-tooth flank position. The result shows that the maximum bending stress under static structural condition is obtained 64.48 MPa.

4.2.2. Contact Pressure result

Contact stress analysis is a tool in ANSYS workbench that can be used to calculate the stresses in contact between two objects. The result obtained in Ansys describes is the maximum and the minimum contact pressure between mating gear teeth. The figure below depicts the maximum pressure value as 40.43 MPa under static structural analysis.

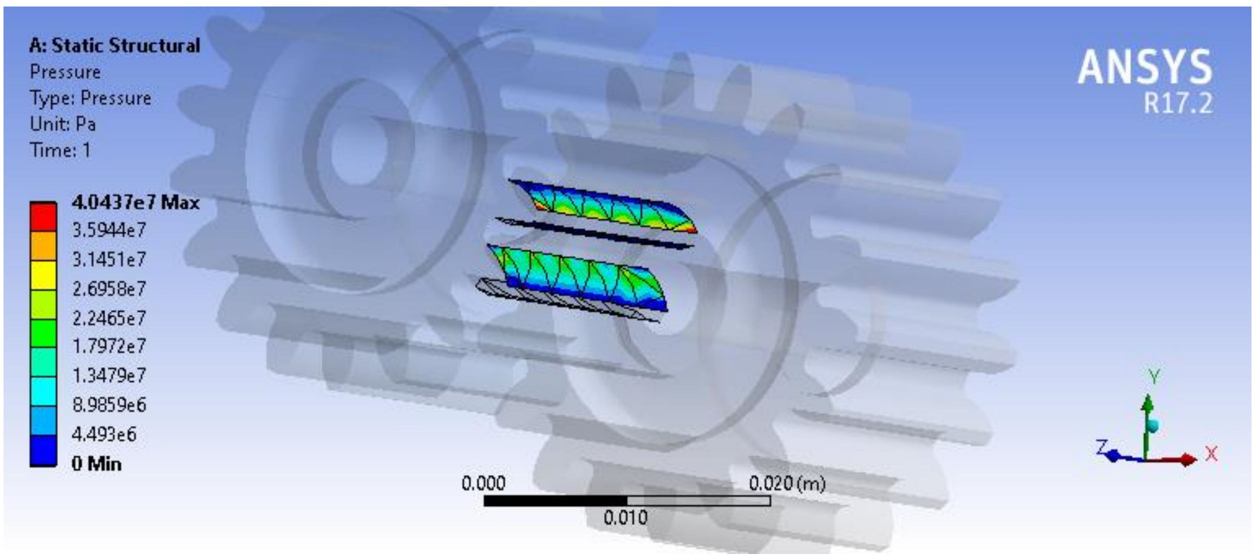


Figure 4- 3 Static Structural: Contact (Pressure) stress Ansys result

The figure depicts the stress distribution at the tooth contact point for a spur gear made of a nanocomposite PEEK polymer matrix. The tooth pitch point is where there is the most contact stress.

The applied torque of 21 Nm results in the maximum contact stress, which is 40.43 MPa under static structural FEM analysis.

Sliding Distance

It can be examined the sliding distance between two items using the sliding distance analysis tool in ANSYS Workbench. The distance between two points on a surface that are sliding past one another is known as the sliding distance. This can be used to assess how the gear wears.

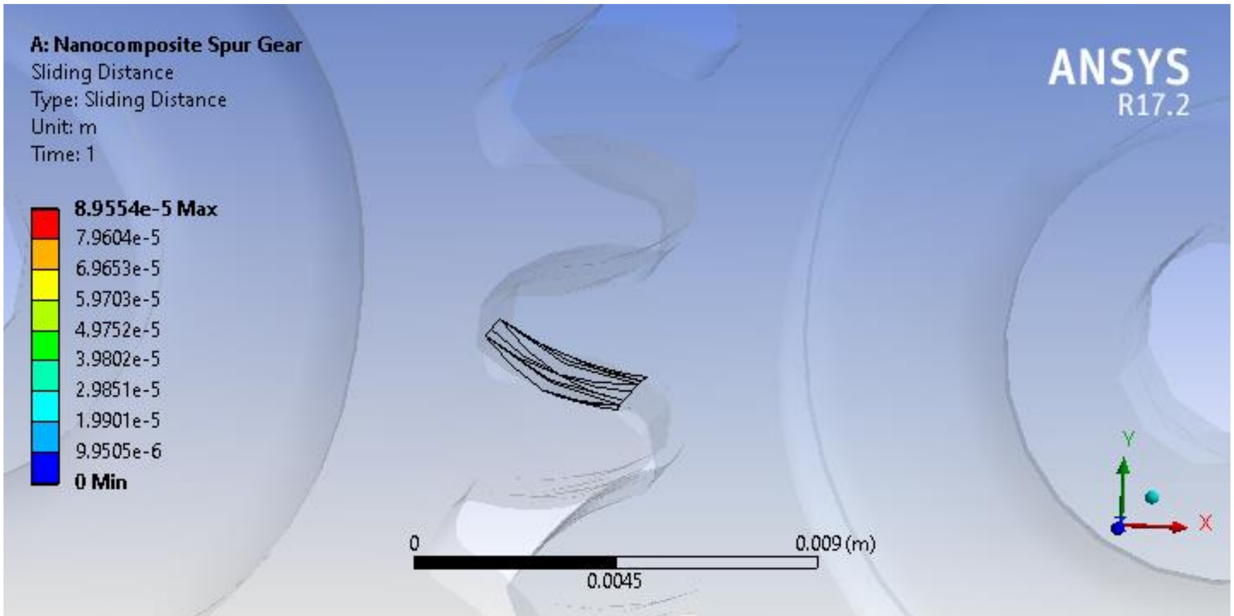


Figure 4- 4 Static Structural: Sliding distance Ansys result

Frictional stress result

The tendency of the two contacting surfaces to slide against one another causes the frictional stress, which is the total of stress components acting in the local x and y directions. Before they begin to slide apart in a frictional contact, the two contacting surfaces can sustain shear loads across their interface up to a particular magnitude. The two surfaces will slide in relation to one another if the shear stress is exceeded. This state is known as sliding.

When a point switches from sticking to sliding or vice versa, it is determined by the sticking/sliding computations.

Frictional stress can be added as an output, but there is a provision to only add units of stress up to the maximum contact friction. Regardless of normal pressure, if the frictional stress surpasses this value, the bodies begin to slide.

Under static structural FEM analysis, the maximum frictional stress is obtained as 12.13 MPa under the moment of 21 Nm.

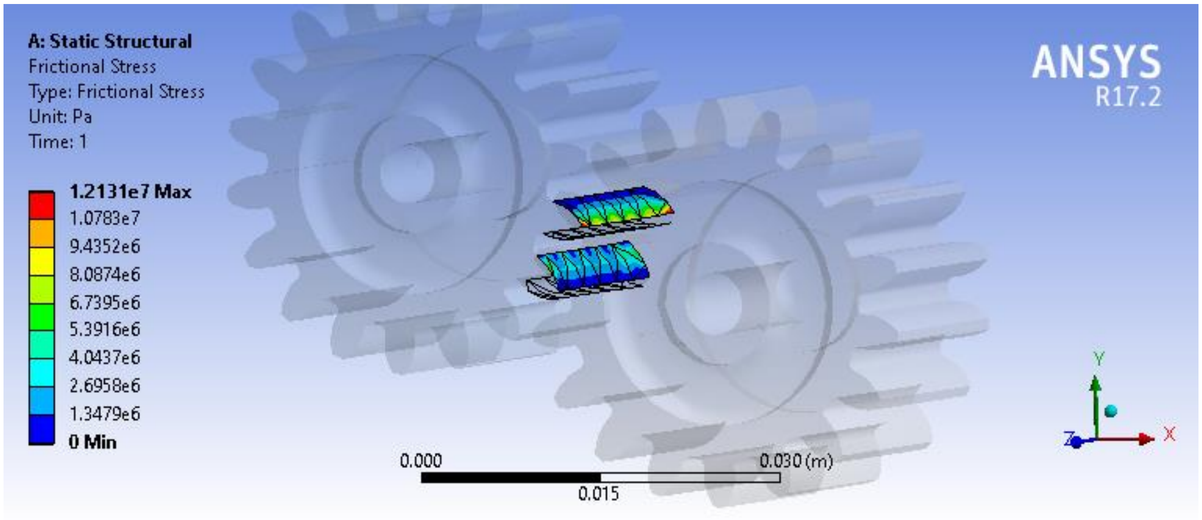


Figure 4- 5 Static Structural: Frictional stress Ansys result

4.2.3. Fatigue Analysis

Fatigue analysis is the process of determining how long a gear will last before it fails due to wear and tear. Wear and tear on equipment can be influenced by a few different things. These consist of:

- The type of gear material used
- The design of the gear teeth

Fatigue analysis in ANSYS Workbench requires the accurate description of the fatigue material properties. This is because, fatigue analysis is empirical and it becomes very difficult to take in to account all materials type. Therefore, in doing fatigue analysis in ANSYS Workbench, users must provide their own fatigue data.

In Ansys Workbench, we can determine the life cycle of the gear before the gear fails to work, we can determine how much damage the gear will sustain until it reaches the gear design cycle and we can also determine the factor of safety of the gear.

Fatigue Life of the gear

Just like any other Workbench contour result, Fatigue Life can be over the entire model or scoped (i.e. parts, surfaces, edges, and vertices). The possible life for the provided fatigue analysis can be seen on this result contour plot. This reflects the number of cycles the part will undergo under constant-amplitude loading before failing from fatigue. This reflects the number of loading blocks till failure if loading is not constant.

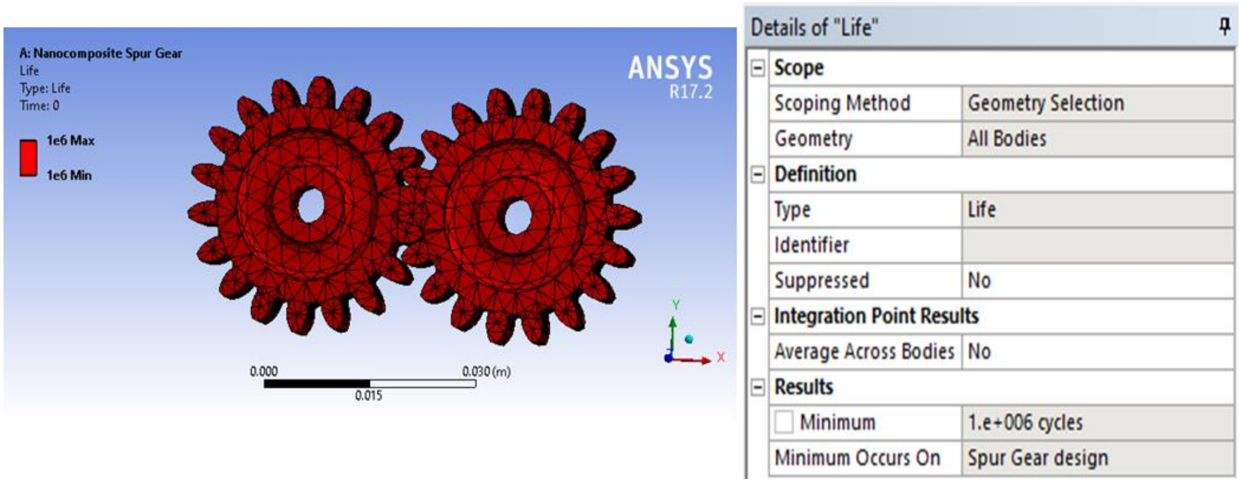


Figure 4- 6 Static Structural: Fatigue life cycle Ansys result

A contour plot of the fatigue damage at a specific design life is called fatigue damage. The design life divided by the available life is the definition of fatigue damage. This outcome might be scoped. Through the Control Panel, the default design life can be changed. Values greater than 1 for fatigue damage imply failure before the intended lifespan is attained.

Safety factor result

Fatigue Safety Factor is a contour plot of the factor of safety with respect to a fatigue failure at a given design life. The maximum Factor of Safety displayed is 15. Like damage and life, this result may be scoped. For Fatigue Safety Factor, values less than one indicate failure before the design life is reached. The result which is 1.3957 greater than one shows that in the current loading condition it can sustain until its design life cycle.

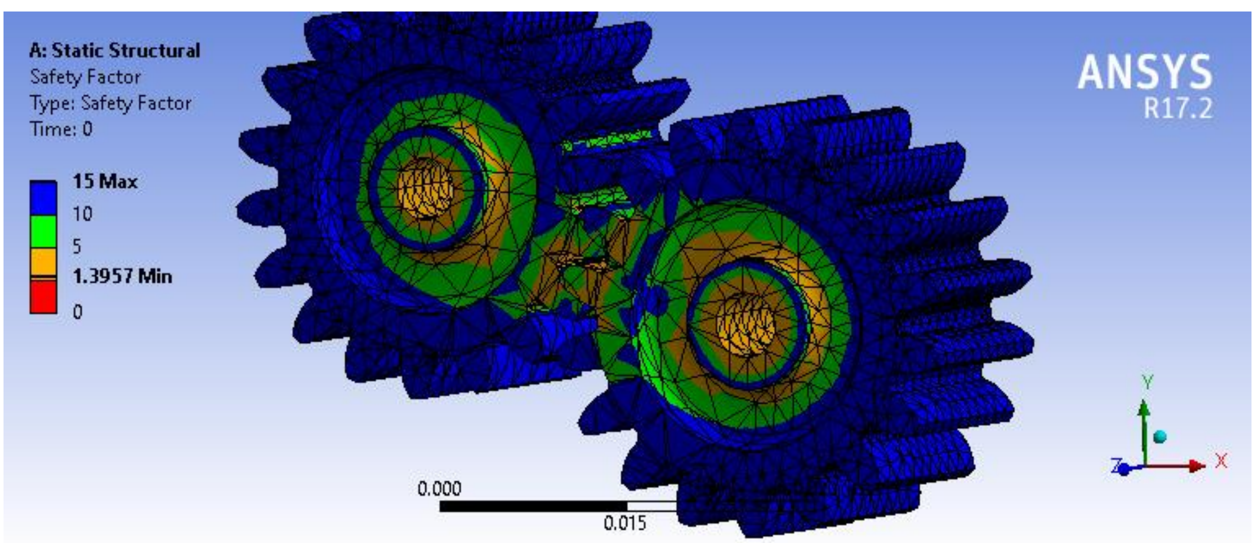


Figure 4- 7 Static Structural: Fatigue safety factor Ansys result

4.3. Dynamic (Transient) Analysis in ANSYS Results

A simple static approach is not sufficient since it will capture the stress distribution only in one of the positions of the two gears.

Dynamic load refers to a load that changes over time in terms of intensity, direction, or point of application. Variable stresses are produced in mechanical components due to dynamic load. The load operating on the gear tooth of a spur gear is variable in point of application but constant in size and direction. Spur gear teeth are thus subjected to varying loads, which result in fatigue failure. Danger may result from a sudden gear tooth failure. Hence, a dynamic study of the spur gear is required.

4.3.1. Bending Stress

The bending moment increases in relation to concentrated load as the load advances from the point of initial meshing to the tip of the tooth, and the bending stress of the tooth root achieves its maximum at the highest point of single-tooth contact.

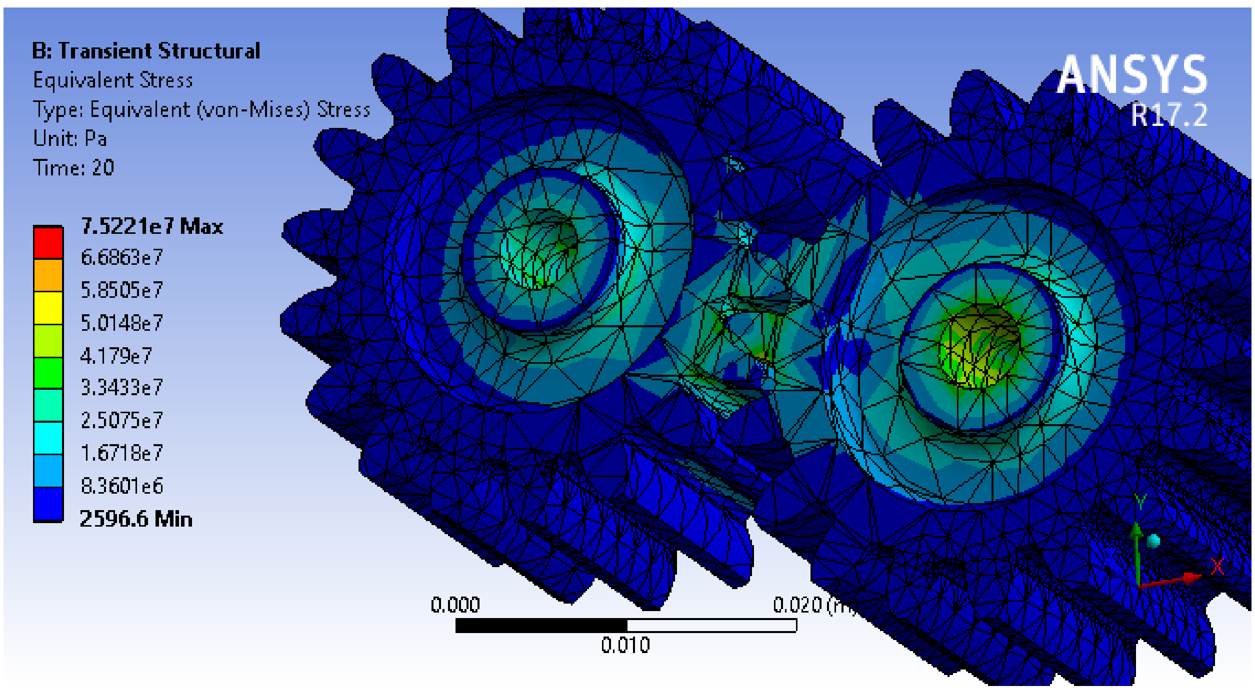


Figure 4- 8 Transient structural: Equivalent (von-Mises) stress

At different point of time, the influence of the bending of gear teeth is different due to the acting position.

Gear tooth failure due to bending fatigue typically starts as a crack initiation at the gear tooth's root region. Cycled loading that stresses the gear tooth beyond the material's endurance limitations is one of the factors that contributes to bending fatigue failures. In the these analysis 20 time steps is used and the minimum stress recorded is at the first time step which is 75.20 MPa while the same magnitude is recorded for the remaining steps which is 75.22 MPa.

The Equivalent (Von-Mises) Stress recorded at different time steps can be seen in the figure below.

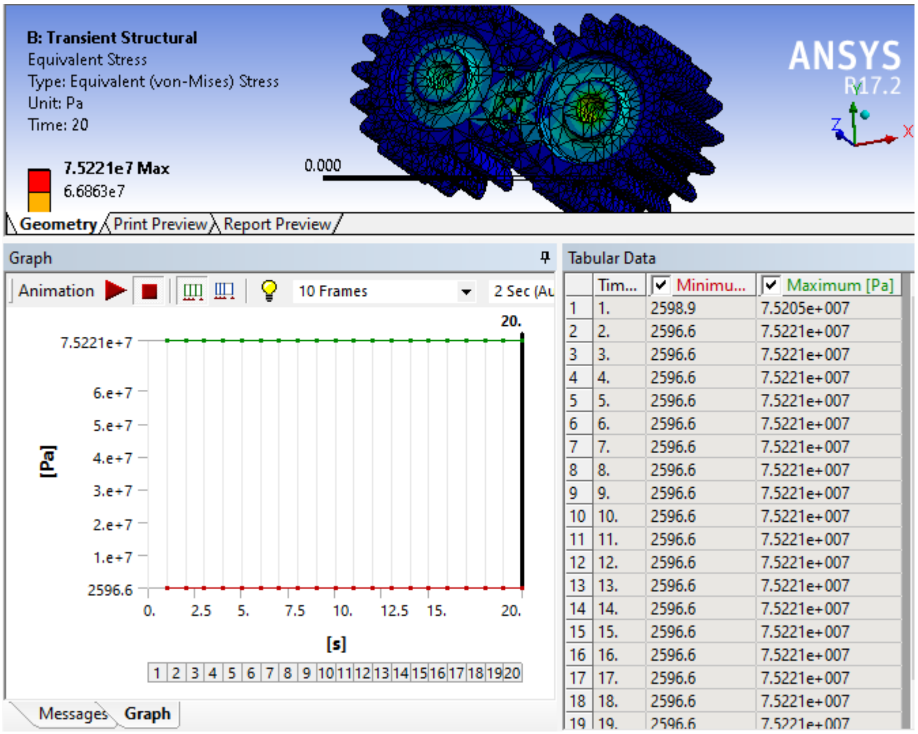


Figure 4- 9 Transient Structural: Equivalent Stress at different time step

4.3.2. Contact stress

The conventional formula only considers one specific point in time and one contact surface for calculating the contact stress in the gear. The lowest point of single-tooth contact has the highest contact stress. The figure below in parallel to red color depicts the peak gear contact stress at the high point of tooth contact.

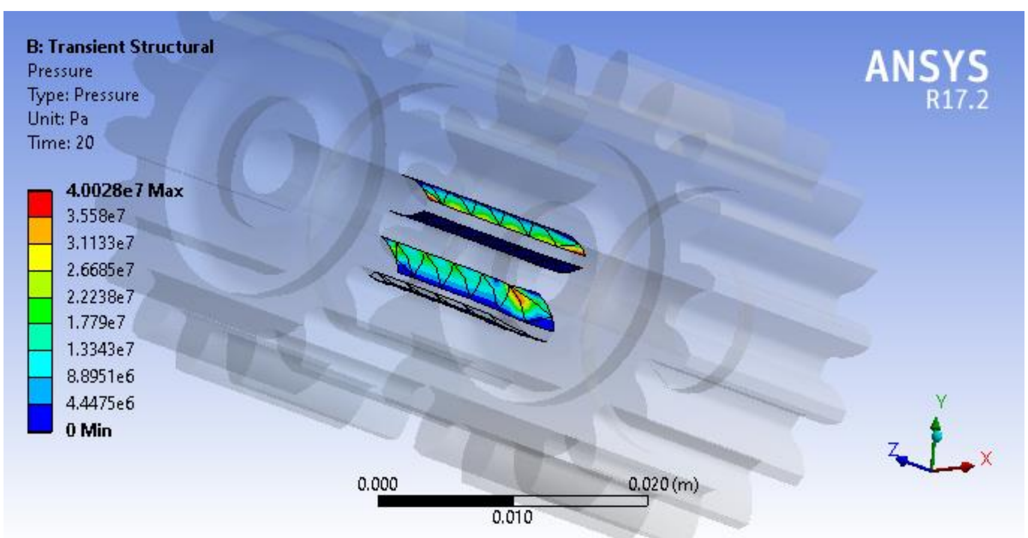


Figure 4- 10 Transient Structural: Pressure ANSYS result

A range of values that accurately describes the contact stress values at various points in time and in various contact positions of the gear tooth is the contact stress estimated using transient dynamics analysis. As it can be seen in the figure below the maximum contact stress varies from 40.027 MPa to 40.03 MPa when the time steps vary. Large contact stress is recorded at the second time step while small contact stress is recorded in the first-time step.

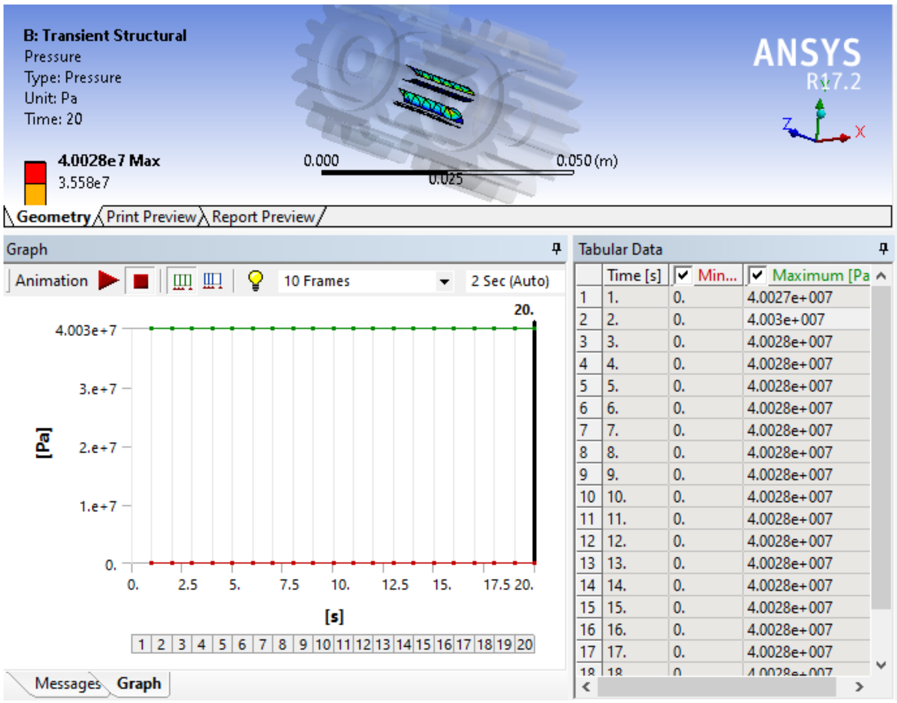


Figure 4- 11 Transient Structural: Contact Stress at different time step

Frictional stress result

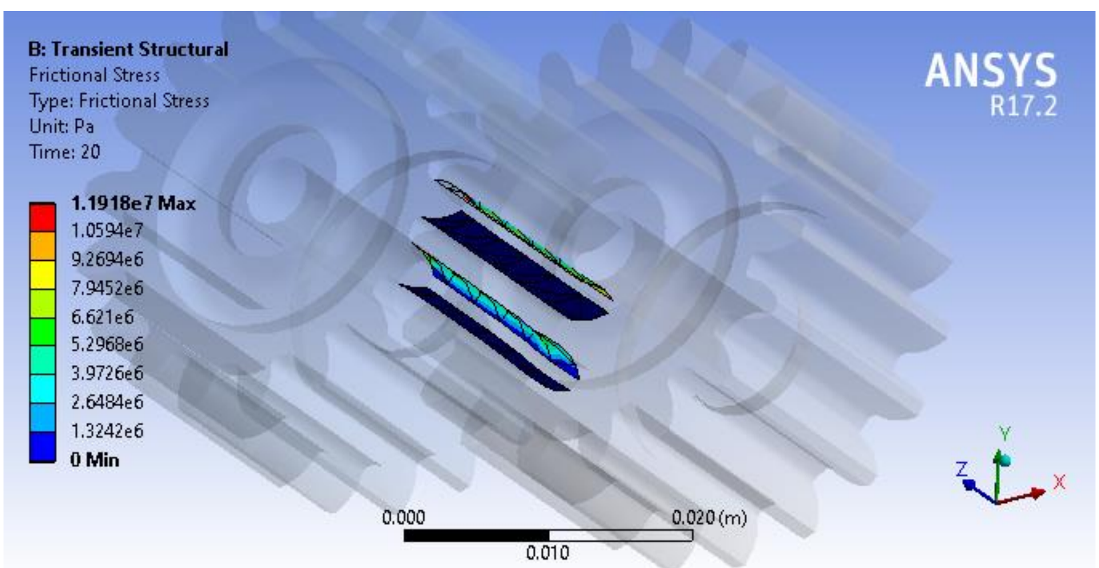


Figure 4- 12 Transient Structural: Frictional Stress ANSYS result

4.3.3. Fatigue

In conditions of dynamic loading, mean values and amplitudes of primary stresses are estimated, along with related Mises stresses, for fatigue failure analysis due to combined loading. The fatigue factor of safety values obtained is 1.196 for this analysis.

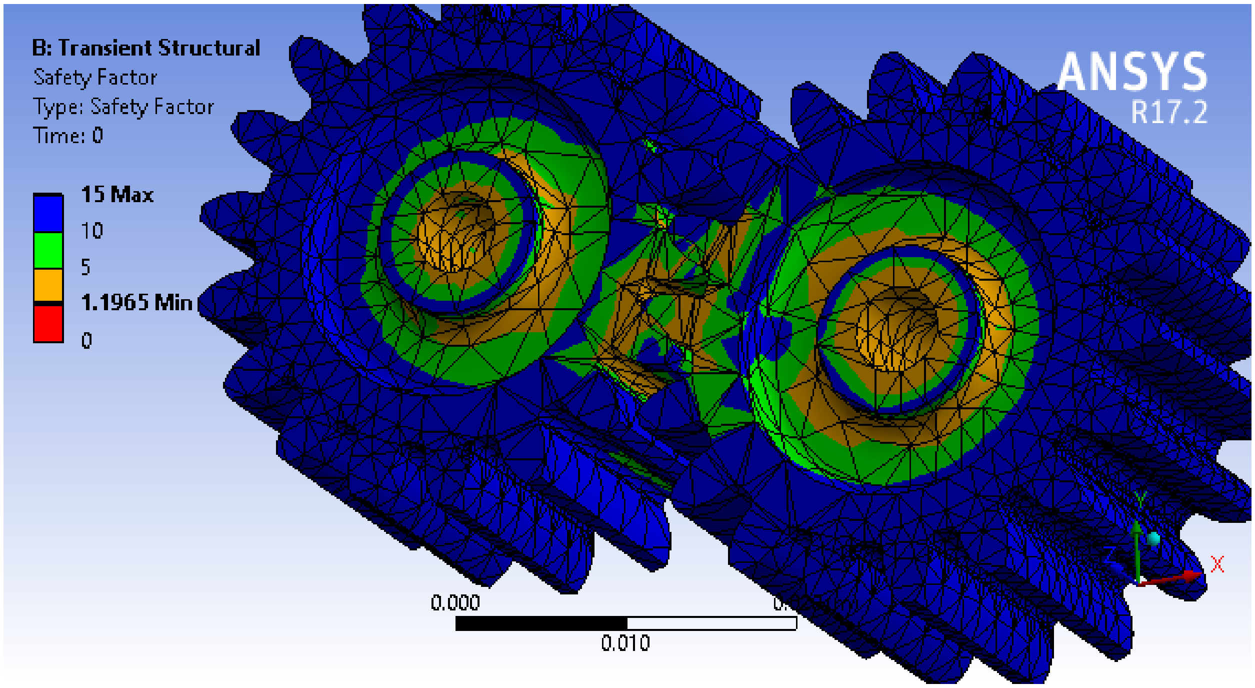


Figure 4- 13 Transient Structural: Safety factor against Fatigue ANSYS result

The advantage of the transient analysis is that it will effectively capture the dynamic impact of moving gears.

In Table 4-2 values of contact pressure, equivalent stress and frictional stress for static structural and transient structural analysis are compared. The static and transient structural analysis loading condition of moment 21 Nm and rotational velocity of 152 rad/s is applied

Table 4- 2 Static and Dynamic (Transient) structural analysis result comparison

APPLIED MOMENT 21 NM & ROTATIONAL VELOCITY 152 RAD/S	CONTACT PRESSURE (MPA)	EQUIV. STRESS VON MISES (MPA)	FRICTIONAL STRESS (MPA)
STATIC STRUCTURAL FEM ANALYSIS	40.43	64.48	12.13
TRANSIENT (DYNAMIC) STRUCTURAL FEM ANALYSIS	40.03	75.22	11.92
RELATIVE DIFFERENCE %	-0.9%	14%	1.7%

In contrast, the table above showed that the contact pressure was roughly the same for static and dynamic or transient analyses. The same is also can be said for frictional stress, where there is only a 1.7% relative difference. And the equivalent (Von-Mises) stress is greater in the transient (dynamic) FEM stress analysis from that of static structural analysis. It is vital to take into account the maximum transient stress value because in the worst-case scenario, the gear system suffers frequent or considerable transient stresses. This is because gears frequently start and stop loading or experience rapid load fluctuations in applications involving power transfer.

In conclusion, reliable and effective gear functioning depends on the study of static and transient stresses in spur gears. Spur gear performance, durability, and lifespan are significantly influenced by both static and transient pressures. Knowing how static and transient loads interact enables the detection of possible failure modes and the application of suitable preventive measures, thereby enhancing the durability and dependability of the gear.

4.4. Comparison of the results obtained with other power transmission gear from literature result

Here under is the comparison of different gear materials manufactured and tested in different condition is presented and compared with the gear material studied in this research paper. The compared gear materials are tested for the use of medium and higher power transition application.

Table 4- 3 Comparison of results obtained with other power transmission gear from other literature result

No.	Gear material	Maximum load bearing capacity	Description	Ref.
1.	PEEK polymer matrix composite material and the nano filler multi-walled carbon nano tube (MWCNT), Zicronia (ZrO_2) and Silica (SiO_2)	Speed 1,450 rpm and torque 21 Nm	Flexural strength 159.88 MPa & Flexural Modulus 4900.65 MPa The maximum contact stress is 87.276 MPa The maximum gear life cycle obtained is 10^6 gear cycles	
2.	0.3% multilayer graphene nanoplatelets (MLNGPs) is added to polyamide 6 (PA6) gear material	Speed 1400 rpm & torque 16 Nm	196000 cycles where its maximum life cycle.	[35]
3.	2 wt% CaCO3 polybutylene terephthalate/ calcium carbonate nanocomposite gears	Speed 1000 rpm & torque 11 Nm	Cycle time at each load level was set to 20 minutes, which was equal to 20000 cycles x 7	[36]

4.	Polyamide 6 gears	Speed 200 rpm & torque 16.53 Nm	the maximum running life of gear is obtained as 4.2 x 10^5	[37]
5.	polyacetal (POM) containing 0.42 wt% nano-sized carbon black (CB) particles	Speed 1500 rpm & torque 8 Nm	The maximum contact stress under the torques of 8 Nm is obtained 40.7 MPa	[38]
6.	Poly(butylene terephthalate) (PBT) and montmorillonite (MMT) were employed as the polymer matrix and nano reinforcement 2 wt% clay	Speed 1000 rpm & torque 11 Nm	the maximum running life of gear is obtained 2.2x10^6 cycle	[39]
7.	3 wt% of nano-CaCO3 polyoxymethylene gear	Speed 645 rpm and torque of 11.2 Nm	The minimum gear life 48,000 revolutions in neat POM gears and the maximum gear life 98,000 revolutions was perceived in POM/3 C nanocomposite gear. The highest flexural strength (130 MPa) and modulus (2813 MPa)	[40]
8.	polyoxymethylene (POM) / carbon black (CB) spur gears	Torque of 14 Nm	The gear life cycle was 12x10^4 cycles and maximum contact stress is 45 MPa	[41]

Chapter 5: Conclusion, Recommendation and Future work

Conclusion

In this research paper the performance of newly developed polymer nanocomposite gear material was investigated. Composite gear fails under high load and high speed working conditions. Failure is mostly brought about by gear tooth wear (adhesive and abrasive wear), gear tooth bending/deformation, and abrupt gear tooth breakage as a result of cyclic stress.

Nano sized particle were added to reinforce PEEK polymer matrix in order to obtain enhanced material property for higher power transmission gear application by replacing conventional gear materials.

The materials are selected by comparing different materials and selecting the outstanding material which specifically satisfy for gear material application. Since variation of additives nano particle to a polymer material gives unique material property while varying the composition of additives because of their distinctive features of the nano particles. Material property is predicted by using machine learning process. Chemical composition consisting of PEEK polymer matrix composite material and the 4% nano filler multi-walled carbon nano tube (MWCNT), 3% Zicronia (ZrO_2) and 5% Silica (SiO_2) by weigh material is obtained and the mechanical property of this material is predicted by artificial neural network (ANN).

After obtaining the material property analytical and FEM analysis has been conducted by using the newly developed material. FEM is used to analyze contact stress and estimate fatigue life of gear and it is performed in FEM Ansys workbench 17.2. The predicted material property is added in to Ansys material database and the contact analysis, fatigue analysis and bending analysis has been conducted. The material gear life cycle is found to be one million cycles with loading condition of 1,450 rpm and 21 Nm torque and the maximum bending stress at this load is recorded for at the transient structural FEM analysis which is 75.22 MPa while in static structural FEM analysis is obtained 64.48 MPa. Whereas for contact and frictional stress close results are obtained.

The results are compared with existing material to assess the capacity of the nanocomposite gear. PEEK material has a higher durability or life cycle and strength. The addition of nano particle reinforcement in to PEEK polymer matrix have improved the life of the gear and higher loads can be tolerated compared to previously developed material. The polymer nanocomposite gear material is appeared to be potential gear material with enhanced material property, good strength and durability for the application of power transmission.

Recommendation

The nano particle reinforced PEEK polymer matrix material is a potential choice for high power transmission gear due to its high strength, stiffness, and resistance to wear and tear. Additionally, its low weight to strength ratio makes it a desirable option for applications such as automotive components.

Nano particle reinforced PEEK polymer matrix material is a good option for the performance of medium load range power transmission of balance shaft gear in automotive application. The material has good mechanical properties. It can withstand high temperatures and harsh engine environment.

Additionally, Machine learning can be used to predict the properties of materials based on data collected from experiments or data sets. This could include predicting the material's physical and chemical properties, including its strength, resilience, and elasticity. In this research it has been observed that ANN tools can be effective in predicting new material properties when used in conjunction with experimental data. It is recommended to utilize this tool for different researches because it is reliability and its cheapest method to develop different materials.

Future Work

In order to validate the findings further experimental research should be conducted to back up the finds in this research. Therefore, the investigation in this research can be extended in making thorough experimental investigation.

The reinforcing geometry effect of nanoparticles has major effect and should be taken in to consideration and examination of the material property should be conducted.

Additionally, in polymer matrix nanocomposite material, thermal softening is a significant problem. The hydrogen bonds that connect the polymer chains weaken as the temperature rises, causing the mechanical characteristics to deteriorate. Further research should be done on the impact of thermal behavior on fatigue life estimation, particularly the impact of lubrication on surface fatigue life.

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Appendix

Appendix A:1-

A:1.1. Comparison material property of different polymer nano-composite material

No.	Material		Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Young's Modulus (MPa)	Impact strength (KJ/m2)	% Elongation	Hardness HV	Material Rank	Reference
	polymer	nanofiller										
1	100% POM	0% CaCO2	-	-	98	2450	-	6.1	-	-	-	[40]
2	97 % POM	3% CaCO2	-	-	130	2720	-	7.4	-	-	-	
3	94% POM	6% CaCO2	-	-	128	2810	-	6.5	-	-	-	
4	91% POM	9% CaCO2	-	-	125	2780	-	6	-	-	-	
1	100% Acetal copolymer (POM-C)	0% Graphene	60	2680	71.23	2578.56	-	80.32	23	-	-	[11]
2	98.5% Acetal copolymer (POM-C)	1.5% Graphene	70	3092.12	83.64	2899.98	-	70.49	18.78	-	-	
1	PA6	zeolite	61.2	2201	81.3	2800	-	12.3	-	-	-	[43]
2	PA6	2.5% Z	75.3	3220	95.7	3495	-	14.2	-	-	-	
3	PA6	5% Z	74	3330	102.1	3550	-	16.2	-	-	-	
4	PA6	7.5% Z	69.1	3450	94.2	3720	-	14	-	-	-	
1	PA6	MLNGPs	72.6	-	-	-	1470		33.24	-	-	[35]
2	PA6	0.1% MLNGPs	75.3	-	-	-	2111.3		25.025	-	-	
3	PA6	0.3% MLNGPs	87.2	-	-	-	2913.3		25.7	-	-	

No.	Material			Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Young's Modulus (MPa)	Impact strength (KJ/m2)	% Elongation	Hardness HV	Material Rank	Reference
	polymer	nanofiller											
4	PA6	0.5% MLNGPs		83.5	-	-	-	2105.9		10.6	-	-	
1	PA6	Clay		-	550	-	-	-	-	-	97.5 rockwell hardness	-	[44]
2	PA6	3% Clay		-	815	-	-	-	-	-	100.2	-	
3	PA6	5% Clay		-	950	-	-	-	-	-	105.3	-	
1	POM	CNT	PTFE	48	1700	-	-	-	-	-	-	-	[45]
2	99.5	0.5	0	60	2350	-	-	-	-	-	-	-	
3	99	1	0	66	2600	-	-	-	-	-	-	-	
4	98	2	0	58	2650	-	-	-	-	-	-	-	
5	95	0	5	48	1650	-	-	-	-	-	-	-	
6	90	0	10	43	1600	-	-	-	-	-	-	-	
7	85	0	15	34	1480	-	-	-	-	-	-	-	
8	89	1	10	65	2700	-	-	-	-	-	-	-	
1	PA6	Clay		53.1	1500	-	-	-	-	-	Shore 68	-	[46]
2	PA6	5% Clay		63.9	3200	-	-	-	-	-	70	-	
1	PP	CNT		18.64	-	-	-	757.43	-	-	-	-	[47]
2	PP	1% CNT		20 yeild	-	-	-	839.98	-	-	-	-	
1	POM	PTFE	CNTs	49	1750	85	2500	-	-	-	-	-	[48]
2	95	5	0	46	1650	83	2410	-	-	-	-	-	
3	90	10	0	43	1600	75	2350	-	-	-	-	-	
4	85	15	0	35	1450	65	2200	-	-	-	-	-	
5	80	20	0	27	1400	55	2100	-	-	-	-	-	

No.	Material: polymer	Material: nanofiller		Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Young's Modulus (MPa)	Impact strength (KJ/m2)	% Elongation	Hardness HV	Material Rank	Reference
6	99	0	1	65.5	2550	121	3650	-	-	-	-	-	
7	94	5	1	65	2590	119	3750	-	-	-	-	-	
8	89	0	1	64.5	2625	112	3800	-	-	-	-	-	
9	84	15	1	58	2259	100	3325	-	-	-	-	-	
10	79	20	1	51	2000	90	3220	-	-	-	-	-	
1	PEEK	-		92	-	156	-	-	-	-	-	-	[49]
2	PEEK	SCF		115	-	186	-	-	-	-	-	-	
3	PEEK	SCF-KH560		118	-	192	-	-	-	-	-	-	
4	PEEK	SCF-SiO_2		126	-	205	-	-	-	-	-	-	
5	PEEK	CS-SCF		107	-	169	-	-	-	-	-	-	
6	PEEK	CS-SCF-KH560		110	-	173	-	-	-	-	-	-	
7	PEEK	CS-SCF-SiO_2		116	-	181	-	-	-	-	-	-	
1	PEEK	3% GNP		66.1	-	-	-	3680	-	3.46	-	-	Error! Reference source not found.
2	PEEK	5% GNP		58.5	-	-	-	3890	-	3.55	-	-	
3	PEEK	3% CNT		62.5	-	-	-	3370	-	2.66	-	-	
4	PEEK	3% CNT		63.4	-	-	-	3770	-	2.41	-	-	
1	PA11	0% MCNT		38	1558.3	-	1687.81	-	-	38.39	-	-	[51]
2	PA11	0.2% MCNT		33.97	1655.03	-	1747.20	-	-	6.73	-	-	
3	PA11	0.3% MCNT		52.5	1874.94	-	2218.55	-	-	8.92	-	-	
4	PA11	0.4% MCNT		51.74	1782.69	-	2263.44	-	-	12.26	-	-	
5	PA11	0.5% MCNT		60.53	1718.91	-	2276.45	-	-	16.76	-	-	
1	Epoxy	0% CNT		52.52	1320	-	-	-	-	6.57	-	-	[52]
2	Epoxy	0.25% CNT		51.47	1593	-	-	-	-	8.01	-	-	

No.	Material		Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Young's Modulus (MPa)	Impact strength (KJ/m2)	% Elongation	Hardness HV	Material Rank	Reference
	polymer	nanofiller										
3	Epoxy	0.5% CNT	50.22	1472	-	-	-	-	7.48	-	-	
4	Epoxy	1% CNT	49.20	1455	-	-	-	-	7.28	-	-	
5	Epoxy	2% CNT	47.40	1370	-	-	-	-	6.81	-	-	
1	PP	0%GO 0%g-MA	22.6	1028	-	-	-	-	48	-	-	[53]
2	PP	0.05% GO 0%g-MA	24.9	1211	-	-	-	-	25.2	-	-	
3	PP	0.05% GO 3%g-MA	26.0	1280	-	-	-	-	27.4	-	-	
4	PP	0.15% GO 0%g-MA	28.4	1336	-	-	-	-	21.5	-	-	
5	PP	0.15% GO 3%g-MA	29.1	1414	-	-	-	-	23.8	-	-	
1	POM	0% CNTs	49	1700	85	2500	-	5.25	-	-	-	[54]
2	POM	0.5% CNTs	59	2350	109	3500	-	5.85	-	-	-	
3	POM	0.25% CNTs	52	1850	94	-	-	5.75	-	-	-	
4	POM	1% CNTs	65	2500	120	-	-	5.88	-	-	-	
5	POM	1.5% CNTs	63	2510	198	-	-	5.85	-	-	-	
6	POM	2% CNTs	57	2515	190	-	-	5.83	-	-	-	

A:1.2. Comparison of PEEK material property of different nano particle reinforcing materials

No.	Material		Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	% Elongation	Density	T^o melting	Ref.
	polymer	nanofiller								
1	100% PEEK	0% MWCNTs	103.9	2840	156	3550	25.6	1.31	346	
2	99% PEEK	1% MWCNTs	109	2225	130	3850	23.6	1.364	349	[63]
3	98% PEEK	2% MWCNTs	108	2300	128	3900	17.2	1.367	348	
4	96% PEEK	4% MWCNTs	110	2360	135	4000	19.8	1.372	347	
1	100% PEEK	0% SCF	65	1100	148	3120	14.17	1.31	344	
2	98% PEEK	2% SCF	70	2100	123	3250	15.40	1.333	347.1	[64]
3	95% PEEK	5% SCF	55	2100	127	3000	16.70	1.347	348.7	
1	PEEK	-	92	2840	156	3550	14.7	1.31	347.7	[50]
2	PEEK	15% SCF	115	2981	186	3650	9.8	1.36	348.5	**Error! Reference source not found.**
3	PEEK	15% SCF-KH560	118	3113	192	3710	6.3	1.36	348.6	
4	PEEK	15% SCF-SiO_2	126	3155	205	3960	7.5	1.35	348	
5	PEEK	10% CS 15% SCF	107	3058	169	3970	6.1	1.41	347.7	
6	PEEK	10% CS 15% SCF-KH560	110	3191	173	4150	6.3	1.41	348	
7	PEEK	10% CS 15% SCF-SiO_2	116	3034	181	4220	5	1.40	347.6	
1	PEEK	0%	106.9	2840	156.41	3150	25.6	1.31	346.6	
2	PEEK	+ 0.3 % Cu	100.9	2981	161.24	3110	17.2	1.324	345.7	
3	PEEK	+ 0.3 % Cu-Zn	94.3	3037	164.13	3380	18.2	1.315	347.3	[65]
4	PEEK	+ 0.3 % SiO2	111 .4	3155	165.48	3510	14.7	1.317	346.9	
5	PEEK	+ 0.3 %CuFe2O4	108.4	3113	158.85	3450	19.8	1.309	343.1	
1	PEEK	-	106.9	2840	166	3130	25.6	1.31	338	
2	PEEK	0.3% CNF	107.8	3034	164	3175	23.6	1.315	338	
3	PEEK	0.3% Cu	100.9	2981	161	3110	17.2	1.324	345.7	
4	PEEK	0.3% $CuFe_2O_4$	108.4	3113	158	3450	19.8	1.309	343.1	
5	PEEK	0.3%SiO_2	111 .4	3155	165	3510	14.7	1.317	346.9	[66]
6	PEEK	7% CNF	91.3	3191	166	3310	3.6	1.344	338	
7	PEEK	7% Cu	104.4	2937	164	3762	14	1.375	339	
8	PEEK	7%SiO_2	83.5	2860	171	3920	4	1.354	338	
9	PEEK	7% $CuFe_2O_4$	102.4	3058	175	4007	6.3	1.370	337	
10	PEEK	10% -	83.9	2620	182	3710	5	1.324	347	

No.	Material		Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	% Elong ation	Densi ty	T° melting	Ref.
	polymer	nanofiller								
		PTFE								
11	PEEK	10% PTFE 0.3% CNF	86.4	2559	186	3960	8.2	1.344	346	
12	PEEK	10% PTFE 0.3% Cu	88.6	2566	192	3970	10.1	1.356	346	
13	PEEK	10% PTFE 0.3% $CuFe_2O_4$	95.5	2744	196	4400	8.2	1.352	346	
14	PEEK	10% PTFE 0.3%SiO_2	91.8	2487	202	4920	7.8	1.341	345	
1	PEEK	0% Expanded graphite (EG)	96.73	3840	156.41	3550	27.09	1.31	347	[67]
2	99.5	0.5%	87.70	4090	152.69	3650	10.37	1.310	346.4	
3	99	1%	83.17	4140	146.44	3710	7.36	1.313	346.9	
4	98	2%	78.21	4160	141.50	3960	5.88	1.318	346.2	
5	97	3%	70.29	4000	130.20	3970	5.03	1.321	345.8	
6	95	5%	62.01	4150	118.19	4400	4	1.326	345.9	
7	93	7%	56.49	4570	111.92	4520	2.72	1.332	344.7	
1	PEEK	0% GNP	105.6	3610	166.2	3110	20.1	1.288	347.7	[51]
2	PEEK	1% GNP	98.6	3710	164.1	3380	8.2	1.292	347.7	
3	PEEK	3% GNP	96.5	3860	151.3	3510	4.5	1.301	348	
4	PEEK	5% GNP	95.4	3810	145.5	3450	4.4	1.313	347.6	
5	PEEK	10% GNP	88.5	5200	132.6	3760	2.2	1.332	348	
1	PEEK	0% CNT	66.2	3150	119.61	3400	3.1	1.324	342	[68]
2	PEEK	1% CNT	62.5	3370	122.25	3920	2.66	1.756	344	
3	PEEK	3% CNT	63.4	3770	130.20	3970	2.41	1.796	344	
1	PEEK	0% Zirconia	80.0	3120	148.00	3600	21.12	1.324	348	[69]
2	PEEK	0.5% ZrO_2	90.6	3260	175.68	3880	18.64	1.346	348	
3	PEEK	1% ZrO_2	96.4	3350	182.68	3980	16.17	1.368	352	
4	PEEK	2% ZrO_2	97.9	3380	186.76	4290	15.40	1.411	358	
5	PEEK	3% ZrO_2	99.6	3410	192.40	4600	14.07	1.455	363	
1	PEEK	0%	89	3900	156	3175	25.6	1.300	338	[60]
2	PEEK	2.5%SiO_2	94	4200	159	3210	23.6	1.334	338	
3	PEEK	5%SiO_2	105	4500	164	3248	17.2	1.368	340	
4	PEEK	7.5%SiO_2	91	4900	179	3271	19.8	1.401	339	
5	PEEK	10%SiO_2	89	5300	185	3310	14.7	1.435	339	
6	PEEK	2.5%Al_2O_3	89	3900	181	3762	3.6	1.367	338	
7	PEEK	5%Al_2O_3	97	4100	222	3920	14	1.434	339	

No.	Material polymer	Material nanofiller	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	% Elongation	Density	T° melting	Ref.
8	PEEK	7.5%Al_2O_3	105	4400	246	4007	4	1.501	338	
9	PEEK	10%Al_2O_3	108	4600	259	4290	6.3	1.568	337	
1	100%PEEK	0%SiO_2 0%GO	90.2	3310	156	3175	48.2	1.324	341.1	
2	90/10/0		91.6	3762	156.79	3248	43.1	1.408	343.7	
3	80/20/0		92.6	3920	155.88	3271	19.4	1.431	342.3	
4	70/30/0		95.9	4007	159.74	3310	10.3	1.463	342.9	
5	69.5/30/0.5		97.4	4262	168.10	3762	11.9	1.624	343.1	[70]
6	69.0/30/1.0		98.6	4455	175.68	3920	12.3	1.748	344.5	
7	68.5/30/1.5		101.5	4617	182.68	4007	12.1	1.851	344.8	
8	68/30/2.0		97.4	4572	186.76	4290	11.5	1.863	345.2	
1	PEEK	0% MoS2	106.9	2840	156.41	3150	25.6	1.308	346.4	
2	PEEK	1% MoS2	108.9	3157	161.24	3110	12.7	1.310	346.9	
3	PEEK	10% MoS2	96.8	3412	164.53	3380	4.7	1.423	346.2	
4	PEEK	10% PTFE	83.9	2620	165.78	3510	5	1.320	345.8	
5	PEEK	20% PTFE	67.7	2159	168.75	3550	5	1.408	345.9	
6	PEEK	30% PTFE	55.1	2011	166.14	3600	4.7	1.463	344.7	
1	PEEK+5% PTFE+0.25% MoS_2		94.2	3080	156	3105	9.9	1.329	346.6	
2	PEEK+5% PTFE+0.50% MoS_2		90.3	3050	155	3150	8.4	1.334	345.9	[71, 72]
3	PEEK+5% PTFE+1.00% MoS_2		86.6	2970	159	3110	7.3	1.348	344.7	
4	PEEK+10%PTFE+0.25%MoS_2		88.5	2770	168	3175	7.6	1.367	346.9	
5	PEEK+10%PTFE+0.50%MoS_2		84.9	2760	175	3248	9.8	1.371	346.2	
6	PEEK+10%PTFE+1.00%MoS_2		79.0	2740	182	3271	6.3	1.375	345.8	
7	PEEK+15%PTFE+0.25%MoS_2		71.2	2400	186	3310	7.5	1.383	342.1	
8	PEEK+15%PTFE+0.50%MoS_2		68.1	2520	192	3762	6.1	1.390	343.6	
9	PEEK+15%PTFE+1.00%MoS_2		66.8	2730	196	3820	4.3	1.40	344.4	
10	PEEK+20%PTFE+0.25%MoS_2		49.2	2160	202	3875	6.0	1.408	346.2	
11	PEEK+20%PTFE+0.50%MoS_2		45.1	2070	222	3948	5.2	1.431	345.4	
12	PEEK+20% PTFE+1.0% MoS_2		42..0	2080	246	3971	4.8	1.463	345.9	
1	PEEK	0% IF-WS_2	77	1475	156.41	3120	80	1.324	457.5	
2	PEEK	0.5%IF-WS_2	85	1530	152.69	3210	32	1.585	462.0	
3	PEEK	1%IF-WS_2	95	1610	146.44	3248	30	1.624	463.4	
4	PEEK	2%IF-WS_2	98	1840	141.50	3271	15	1.748	470.1	[73]
5	PEEK	4%IF-WS_2	90	1780	130.20	3310	17	1.851	470.3	
6	PEEK	8%IF-WS_2	85	1750	118.19	3351	13	1.863	473.8	

A:1.3. Chemical (Material) Composition of different gear materials for Input

	Chemical composition																			
No.	**PEEK**	**CNT**	**MW CNT**	**SiO_2**	**CNF**	**GNP**	**GO**	**ZrO_2**	**Al_2O_3**	**PTFE**	**MoS_2**	**EG**	**Cu**	**Cu Fe_2O_4**	**Cu-Zn**	**SCF**	**SCF-H560**	**SCF-SiO_2**	**CS**	**IF-WS_2**
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0.99	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.98	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.96	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0.98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0
5	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0
6	0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0	0
7	0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0
8	0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0
9	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0.1	0
10	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0.1	0
11	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0.1	0
12	0.997	0	0	0	0	0	0	0	0	0	0	0	0.003	0	0	0	0	0	0	0
13	0.997	0	0	0	0	0	0	0	0	0	0	0	0	0	0.003	0	0	0	0	0
14	0.997	0	0	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0.997	0	0	0	0	0	0	0	0	0	0	0	0	0.003	0	0	0	0	0	0
16	0.997	0	0	0	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0.93	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0.93	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0
19	0.93	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0.93	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0
21	0.9	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0
22	0.897	0	0	0	0.003	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0

	Chemical composition																			
No.	PEEK	CNT	MW CNT	SiO_2	CNF	GNP	GO	ZrO_2	Al_2O_3	PTFE	MoS_2	EG	Cu	Cu Fe_2O_4	Cu-Zn	SCF	SCF-H560	SCF-SiO_2	CS	IF-WS_2
23	0.897	0	0	0	0	0	0	0	0	0.1	0	0	0.003	0	0	0	0	0	0	0
24	0.897	0	0	0	0	0	0	0	0	0.1	0	0	0	0.003	0	0	0	0	0	0
25	0.897	0	0	0.003	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0
26	0.995	0	0	0	0	0	0	0	0	0	0	0.005	0	0	0	0	0	0	0	0
27	0.99	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0
28	0.98	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0	0	0	0
29	0.97	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0
30	0.95	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0	0
31	0.93	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0
32	0.99	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0.97	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0.95	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0.9	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0.99	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0.97	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0.995	0	0	0	0	0	0	0.005	0	0	0	0	0	0	0	0	0	0	0	0
39	0.99	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
40	0.98	0	0	0	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
41	0.97	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
42	0.975	0	0	0.025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0.95	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0.925	0	0	0.075	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0.9	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0.975	0	0	0	0	0	0	0	0.025	0	0	0	0	0	0	0	0	0	0	0
47	0.95	0	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0

	Chemical composition																			
No.	**PEEK**	**CNT**	**MW CNT**	**SiO_2**	**CNF**	**GNP**	**GO**	**ZrO_2**	**Al_2O_3**	**PTFE**	**MoS_2**	**EG**	**Cu**	**Cu Fe_2O_4**	**Cu-Zn**	**SCF**	**SCF-H560**	**SCF-SiO_2**	**CS**	**IF-WS_2**
48	0.925	0	0	0	0	0	0	0	0.075	0	0	0	0	0	0	0	0	0	0	0
49	0.9	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0
50	0.9	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0.8	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0.7	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0.695	0	0	0.3	0	0	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0.69	0	0	0.3	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0.685	0	0	0.3	0	0	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0.68	0	0	0.3	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0.99	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0
58	0.9	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0
59	0.9	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0
60	0.8	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0
61	0.7	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0
62	0.9475	0	0	0	0	0	0	0	0	0.05	0.0025	0	0	0	0	0	0	0	0	0
63	0.945	0	0	0	0	0	0	0	0	0.05	0.005	0	0	0	0	0	0	0	0	0
64	0.94	0	0	0	0	0	0	0	0	0.05	0.01	0	0	0	0	0	0	0	0	0
65	0.8975	0	0	0	0	0	0	0	0	0.1	0.0025	0	0	0	0	0	0	0	0	0
66	0.895	0	0	0	0	0	0	0	0	0.1	0.005	0	0	0	0	0	0	0	0	0
67	0.89	0	0	0	0	0	0	0	0	0.1	0.01	0	0	0	0	0	0	0	0	0
68	0.8475	0	0	0	0	0	0	0	0	0.15	0.0025	0	0	0	0	0	0	0	0	0
69	0.845	0	0	0	0	0	0	0	0	0.15	0.005	0	0	0	0	0	0	0	0	0
70	0.84	0	0	0	0	0	0	0	0	0.15	0.01	0	0	0	0	0	0	0	0	0
71	0.7975	0	0	0	0	0	0	0	0	0.2	0.0025	0	0	0	0	0	0	0	0	0
72	0.795	0	0	0	0	0	0	0	0	0.2	0.005	0	0	0	0	0	0	0	0	0

	Chemical composition																			
No.	**PEEK**	**CNT**	**MW CNT**	**SiO_2**	**CNF**	**GNP**	**GO**	**ZrO_2**	**Al_2O_3**	**PTFE**	**MoS_2**	**EG**	**Cu**	**Cu Fe_2O_4**	**Cu-Zn**	**SCF**	**SCF-H560**	**SCF-SiO_2**	**CS**	**IF-WS_2**
73	0.79	0	0	0	0	0	0	0	0	0.2	0.01	0	0	0	0	0	0	0	0	0
74	0.995	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.005
75	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01
76	0.98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02
77	0.96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04
78	0.92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08

A:1.4. Material property for different material compositions

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T^o melting
0	103.90	2840.00	156.00	3550.00	1.31	25.60	346.00
1	109.00	2225.00	130.00	3850.00	1.36	23.60	349.00
2	108.00	2300.00	128.00	3900.00	1.37	17.20	348.00
3	110.00	2360.00	135.00	4000.00	1.37	19.80	347.00
4	70.00	2100.00	123.00	3250.00	1.33	15.40	347.10
5	55.00	2100.00	127.00	3000.00	1.35	16.70	348.70
6	115.00	2981.00	186.00	3650.00	1.36	9.80	348.50
7	118.00	3113.00	192.00	3710.00	1.36	6.30	348.60
8	126.00	3155.00	205.00	3960.00	1.35	7.50	348.00
9	107.00	3058.00	169.00	3970.00	1.41	6.10	347.70
10	110.00	3191.00	173.00	4150.00	1.41	6.30	348.00
11	116.00	3034.00	181.00	4220.00	1.40	5.00	347.60
12	100.90	2981.00	161.00	3110.00	1.32	17.20	345.70
13	94.30	3037.00	164.00	3380.00	1.32	18.20	347.30
14	111.40	3155.00	165.00	3510.00	1.32	14.70	346.90
15	108.40	3113.00	158.00	3450.00	1.31	19.80	343.10
16	107.80	3034.00	164.00	3175.00	1.32	23.60	338.00
17	91.30	3191.00	166.00	3310.00	1.34	3.60	338.00
18	104.40	2937.00	164.00	3762.00	1.38	14.00	339.00
19	83.50	2860.00	171.00	3920.00	1.35	4.00	338.00
20	102.40	3058.00	175.00	4007.00	1.37	6.30	337.00
21	83.90	2620.00	182.00	3710.00	1.32	5.00	347.00
22	86.40	2559.00	186.00	3960.00	1.34	8.20	346.00
23	88.60	2566.00	192.00	3970.00	1.36	10.10	346.00
24	95.50	2744.00	196.00	4400.00	1.35	8.20	346.00
25	91.80	2487.00	202.00	4920.00	1.34	7.80	345.00
26	87.70	4090.00	152.69	3650.00	1.31	10.37	346.40
27	83.17	4140.00	146.44	3710.00	1.31	7.36	346.90
28	78.21	4160.00	141.50	3960.00	1.32	5.88	346.20
29	70.29	4000.00	130.20	3970.00	1.32	5.03	345.80
30	62.01	4150.00	118.19	4400.00	1.33	4.00	345.90
31	56.49	4570.00	111.92	4520.00	1.33	2.72	344.70

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T^o melting
32	98.60	3710.00	164.10	3380.00	1.29	8.20	347.70
33	96.50	3860.00	151.30	3510.00	1.30	4.50	348.00
34	95.40	3810.00	145.50	3450.00	1.31	4.40	347.60
35	88.50	5200.00	132.60	3760.00	1.33	2.20	348.00
36	62.50	3370.00	122.25	3920.00	1.76	2.66	344.00
37	63.40	3770.00	130.20	3970.00	1.80	2.41	344.00
38	90.60	3260.00	175.68	3880.00	1.35	18.64	348.00
39	96.40	3350.00	182.68	3980.00	1.37	16.17	352.00
40	97.90	3380.00	186.76	4290.00	1.41	15.40	358.00
41	99.60	3410.00	192.40	4600.00	1.46	14.07	363.00
42	94.00	4200.00	159.00	3210.00	1.33	23.60	338.00
43	105.00	4500.00	164.00	3248.00	1.37	17.20	340.00
44	91.00	4900.00	179.00	3271.00	1.40	19.80	339.00
45	89.00	5300.00	185.00	3310.00	1.44	14.70	339.00
46	89.00	3900.00	181.00	3762.00	1.37	3.60	338.00
47	97.00	4100.00	222.00	3920.00	1.43	14.00	339.00
48	105.00	4400.00	246.00	4007.00	1.50	4.00	338.00
49	108.00	4600.00	259.00	4290.00	1.57	6.30	337.00
50	91.60	3762.00	156.79	3248.00	1.41	43.10	343.70
51	92.60	3920.00	155.88	3271.00	1.43	19.40	342.30
52	95.90	4007.00	159.74	3310.00	1.46	10.30	342.90
53	97.40	4262.00	168.10	3762.00	1.62	11.90	343.10
54	98.60	4455.00	175.68	3920.00	1.75	12.30	344.50
55	101.50	4617.00	182.68	4007.00	1.85	12.10	344.80
56	97.40	4572.00	186.76	4290.00	1.86	11.50	345.20
57	108.90	3157.00	161.24	3110.00	1.31	12.70	346.90
58	96.80	3412.00	164.53	3380.00	1.42	4.70	346.20
59	83.90	2620.00	165.78	3510.00	1.32	5.00	345.80
60	67.70	2159.00	168.75	3550.00	1.41	5.00	345.90
61	55.10	2011.00	166.14	3600.00	1.46	4.70	344.70
62	94.20	3080.00	156.00	3105.00	1.33	9.90	346.60
63	90.30	3050.00	155.00	3150.00	1.33	8.40	345.90
64	86.60	2970.00	159.00	3110.00	1.35	7.30	344.70

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T^o melting
65	88.50	2770.00	168.00	3175.00	1.37	7.60	346.90
66	84.90	2760.00	175.00	3248.00	1.37	9.80	346.20
67	79.00	2740.00	182.00	3271.00	1.38	6.30	345.80
68	71.20	2400.00	186.00	3310.00	1.38	7.50	342.10
69	68.10	2520.00	192.00	3762.00	1.39	6.10	343.60
70	66.80	2730.00	196.00	3820.00	1.40	4.30	344.40
71	49.20	2160.00	202.00	3875.00	1.41	6.00	346.20
72	45.10	2070.00	222.00	3948.00	1.43	5.20	345.40
73	42.00	2080.00	246.00	3971.00	1.46	4.80	345.90
74	85.00	1530.00	152.69	3210.00	1.59	32.00	462.00
75	95.00	1610.00	146.44	3248.00	1.62	30.00	463.40
76	98.00	1840.00	141.50	3271.00	1.75	15.00	470.10
77	90.00	1780.00	130.20	3310.00	1.85	17.00	470.30
78	85.00	1750.00	118.19	3351.00	1.86	13.00	473.80

A:1.5. New concept material Chemical (Material) Composition of different gear materials for prediction

	Chemical composition																			
No.	PEEK	CNT	MW CNT	SiO_2	CNF	GNP	GO	ZrO_2	Al_2O_3	PTFE	MoS_2	EG	Cu	Cu Fe_2O_4	Cu-Zn	SCF	SCF-H560	SCF-SiO_2	CS	IF-WS_2
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0.96	0	0.01	0.02	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
2	0.955	0	0.01	0.025	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
3	0.93	0	0.01	0.05	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
4	0.905	0	0.01	0.075	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
5	0.88	0	0.01	0.1	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
6	0.78	0	0.01	0.2	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
7	0.68	0	0.01	0.3	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
8	0.94	0	0.02	0.02	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
9	0.935	0	0.02	0.025	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
10	0.91	0	0.02	0.05	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
11	0.885	0	0.02	0.075	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
12	0.86	0	0.02	0.1	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
13	0.76	0	0.02	0.2	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
14	0.66	0	0.02	0.3	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
15	0.91	0	0.04	0.02	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0

	Chemical composition																			
No.	**PEEK**	**CNT**	**MW CNT**	**SiO_2**	**CNF**	**GNP**	**GO**	**ZrO_2**	**Al_2O_3**	**PTFE**	**MoS_2**	**EG**	**Cu**	**Cu Fe_2O_4**	**Cu-Zn**	**SCF**	**SCF-H560**	**SCF-SiO_2**	**CS**	**IF-WS_2**
16	0.905	0	0.04	0.025	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
17	0.88	0	0.04	0.05	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
18	0.855	0	0.04	0.075	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
19	0.83	0	0.04	0.1	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
20	0.73	0	0.04	0.2	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
21	0.63	0	0.04	0.3	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
22	0.95	0	0.01	0.02	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
23	0.945	0	0.01	0.025	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
24	0.92	0	0.01	0.05	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
25	0.895	0	0.01	0.075	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
26	0.87	0	0.01	0.1	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
27	0.77	0	0.01	0.2	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
28	0.67	0	0.01	0.3	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
29	0.94	0	0.01	0.02	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
30	0.935	0	0.01	0.025	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
31	0.91	0	0.01	0.05	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
32	0.885	0	0.01	0.075	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
33	0.86	0	0.01	0.1	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0

	Chemical composition																			
No.	PEEK	CNT	MW CNT	SiO_2	CNF	GNP	GO	ZrO_2	Al_2O_3	PTFE	MoS_2	EG	Cu	Cu Fe_2O_4	Cu-Zn	SCF	SCF-H560	SCF-SiO_2	CS	IF-WS_2
34	0.76	0	0.01	0.2	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
35	0.66	0	0.01	0.3	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
36	0.95	0	0.02	0.02	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
37	0.945	0	0.02	0.025	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
38	0.92	0	0.02	0.05	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
39	0.895	0	0.02	0.075	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
40	0.87	0	0.02	0.1	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
41	0.77	0	0.02	0.2	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
42	0.67	0	0.02	0.3	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
43	0.93	0	0.02	0.02	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
44	0.925	0	0.02	0.025	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
45	0.9	0	0.02	0.05	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
46	0.875	0	0.02	0.075	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
47	0.85	0	0.02	0.1	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
48	0.75	0	0.02	0.2	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0
49	0.65	0	0.02	0.3	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0

A:1.6. Predicted Material property for different % of MWCNT, ZrO2 and SiO2 PEEK material compositions

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T° melting
0	81.92	2899.39	156.27	3364.77	1.86	7.92	355.66
1	93.41	3159.72	160.37	4432.31	1.86	10.87	360.24
2	93.32	3264.22	161.03	4429.99	1.86	10.83	359.21
3	92.84	3646.35	163.59	4392.18	1.86	10.90	355.33
4	92.47	3805.80	164.96	4313.36	1.86	11.43	353.10
5	92.55	3781.21	165.44	4200.40	1.86	12.40	352.10
6	99.87	2735.29	165.47	3711.65	1.83	20.10	354.96
7	107.98	3194.78	167.93	3555.10	1.77	27.03	351.43
8	102.13	2918.57	159.95	4836.78	1.86	16.21	370.21
9	102.12	2982.96	160.44	4837.21	1.86	16.13	369.06
10	101.99	3193.99	162.20	4833.13	1.86	16.05	364.75
11	101.82	3222.37	162.90	4818.27	1.86	16.50	362.53
12	101.80	3084.52	162.76	4790.10	1.86	17.46	362.12
13	104.93	2031.01	158.25	4444.26	1.83	25.06	372.80
14	106.68	2247.02	153.94	3829.70	1.78	30.32	369.53
15	106.73	3398.27	158.13	4897.18	1.86	21.37	381.89
16	106.84	3460.61	158.51	4898.01	1.86	21.21	380.62
17	107.40	3660.62	159.88	4900.65	1.86	20.65	375.64
18	108.04	3680.76	160.50	4901.41	1.86	20.50	372.98
19	108.87	3516.85	160.54	4900.72	1.86	20.83	372.74
20	112.92	1967.16	155.40	4875.15	1.83	26.66	395.47
21	112.54	1687.53	146.19	4707.29	1.78	32.13	415.36
22	100.89	3071.86	159.25	4727.40	1.86	18.60	363.83

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T^o melting
23	100.73	3149.64	159.59	4721.79	1.86	18.55	362.71
24	99.78	3450.18	160.58	4677.90	1.86	18.58	358.38
25	98.79	3604.07	160.50	4603.11	1.86	19.06	355.80
26	98.04	3618.29	159.60	4492.27	1.86	19.98	354.64
27	100.64	2731.16	154.36	3865.27	1.83	27.12	359.81
28	104.20	3026.73	152.31	3537.05	1.77	32.65	359.35
29	103.23	2962.74	159.19	4799.62	1.86	26.07	367.42
30	102.95	3028.62	159.23	4792.78	1.86	26.05	366.40
31	101.47	3315.04	158.83	4745.24	1.86	26.05	362.20
32	100.01	3512.66	157.51	4669.08	1.86	26.28	359.44
33	98.80	3599.96	155.51	4556.65	1.86	26.80	358.06
34	99.88	2881.13	146.59	3900.29	1.84	31.95	364.94
35	101.81	2959.43	141.55	3537.01	1.78	36.32	369.24
36	93.76	3068.97	161.39	4639.20	1.86	9.01	363.94
37	93.85	3169.83	162.20	4646.43	1.86	8.94	362.91
38	94.33	3510.91	165.56	4664.70	1.86	8.87	359.21
39	94.97	3578.36	167.79	4657.66	1.86	9.26	357.46
40	96.01	3406.17	169.10	4628.86	1.86	10.10	357.30
41	104.60	2038.24	169.91	4318.92	1.83	17.65	366.19
42	110.95	2252.81	169.71	3916.98	1.77	24.40	360.61
43	105.54	2690.28	159.64	4880.06	1.86	24.33	376.89
44	105.41	2734.85	159.80	4879.13	1.86	24.29	375.87
45	104.71	2903.41	159.99	4871.03	1.86	24.27	371.77
46	103.97	2971.47	159.29	4855.49	1.86	24.54	369.32
47	103.40	2927.51	157.86	4828.64	1.86	25.19	368.54

No.	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural Modulus (MPa)	Density (g/cm^3)	% Elong-ation	T° melting
48	104.49	2131.09	149.35	4475.50	1.84	30.85	379.72
49	104.15	2290.78	142.32	3799.45	1.78	34.89	380.64
50	91.60	3762.00	156.79	3248.00	1.41	43.10	343.70
51	92.60	3920.00	155.88	3271.00	1.43	19.40	342.30
52	95.90	4007.00	159.74	3310.00	1.46	10.30	342.90
53	97.40	4262.00	168.10	3762.00	1.62	11.90	343.10
54	98.60	4455.00	175.68	3920.00	1.75	12.30	344.50
55	101.50	4617.00	182.68	4007.00	1.85	12.10	344.80
56	97.40	4572.00	186.76	4290.00	1.86	11.50	345.20
57	108.90	3157.00	161.24	3110.00	1.31	12.70	346.90
58	96.80	3412.00	164.53	3380.00	1.42	4.70	346.20
59	83.90	2620.00	165.78	3510.00	1.32	5.00	345.80
60	67.70	2159.00	168.75	3550.00	1.41	5.00	345.90
61	55.10	2011.00	166.14	3600.00	1.46	4.70	344.70
62	94.20	3080.00	156.00	3105.00	1.33	9.90	346.60
63	90.30	3050.00	155.00	3150.00	1.33	8.40	345.90
64	86.60	2970.00	159.00	3110.00	1.35	7.30	344.70
65	88.50	2770.00	168.00	3175.00	1.37	7.60	346.90
66	84.90	2760.00	175.00	3248.00	1.37	9.80	346.20
67	79.00	2740.00	182.00	3271.00	1.38	6.30	345.80
68	71.20	2400.00	186.00	3310.00	1.38	7.50	342.10
69	68.10	2520.00	192.00	3762.00	1.39	6.10	343.60
70	66.80	2730.00	196.00	3820.00	1.40	4.30	344.40
71	49.20	2160.00	202.00	3875.00	1.41	6.00	346.20
72	45.10	2070.00	222.00	3948.00	1.43	5.20	345.40
73	42.00	2080.00	246.00	3971.00	1.46	4.80	345.90
74	85.00	1530.00	152.69	3210.00	1.59	32.00	462.00
75	95.00	1610.00	146.44	3248.00	1.62	30.00	463.40
76	98.00	1840.00	141.50	3271.00	1.75	15.00	470.10
77	90.00	1780.00	130.20	3310.00	1.85	17.00	470.30
78	85.00	1750.00	118.19	3351.00	1.86	13.00	473.80

Appendix A:2- ANN training and simulation computer program script

MATLAB code to train ANN

```
% This script assumes these variables are defined:
%
%   Input - input data.
%   Output - target data.

x = Input;
t = Output;
% Choose a Training Function
% For a list of all training functions type: help nntrain
% 'trainlm' is usually fastest.
% 'trainbr' takes longer but may be better for challenging problems.
% 'trainscg' uses less memory. Suitable in low memory situations.
trainFcn = 'trainlm';  % Levenberg-Marquardt backpropagation.

% Create a Fitting Network
hiddenLayerSize = 20;
net = fitnet(hiddenLayerSize,trainFcn);
% Choose Input and Output Pre/Post-Processing Functions
% For a list of all processing functions type: help nnprocess
net.input.processFcns = {'removeconstantrows','mapminmax'};
net.output.processFcns = {'removeconstantrows','mapminmax'};

% Setup Division of Data for Training, Validation, Testing
% For a list of all data division functions type: help nndivision
net.divideFcn = 'dividerand';  % Divide data randomly
net.divideMode = 'sample';  % Divide up every sample
```

```
net.divideParam.trainRatio = 70/100;
net.divideParam.valRatio = 15/100;
net.divideParam.testRatio = 15/100;
% Choose a Performance Function
% For a list of all performance functions type: help nnperformance
net.performFcn = 'mse';  % Mean Squared Error

% Choose Plot Functions
% For a list of all plot functions type: help nnplot
net.plotFcns = {'plotperform','plottrainstate','ploterrhist', ...
   'plotregression', 'plotfit'};
% Train the Network
[net,tr] = train(net,x,t);

% Test the Network
y = net(x);
e = gsubtract(t,y);
performance = perform(net,t,y)
% Recalculate Training, Validation and Test Performance
trainTargets = t .* tr.trainMask{1};
valTargets = t .* tr.valMask{1};
testTargets = t .* tr.testMask{1};
trainPerformance = perform(net,trainTargets,y)
valPerformance = perform(net,valTargets,y)
testPerformance = perform(net,testTargets,y)

% View the Network
view(net)
% Plots
```

```
% Uncomment these lines to enable various plots.
%figure, plotperform(tr)
%figure, plottrainstate(tr)
%figure, ploterrhist(e)
%figure, plotregression(t,y)
%figure, plotfit(net,x,t)
% Deployment
% Change the (false) values to (true) to enable the following code blocks.
% See the help for each generation function for more information.
if (false)
  % Generate MATLAB function for neural network for application
  % deployment in MATLAB scripts or with MATLAB Compiler and Builder
  % tools, or simply to examine the calculations your trained neural
  % network performs.
  genFunction(net,'myNeuralNetworkFunction');
  y = myNeuralNetworkFunction(x);
end
if (false)
  % Generate a matrix-only MATLAB function for neural network code
  % generation with MATLAB Coder tools.
  genFunction(net,'myNeuralNetworkFunction','MatrixOnly','yes');
  y = myNeuralNetworkFunction(x);
end
if (false)
  % Generate a Simulink diagram for simulation or deployment with.
  % Simulink Coder tools.
  gensim(net);
end
```

Appendix A:3-

Table 1 Values of the Lewis Form Factor Y (These Values Are for a Normal Pressure Angle of 20°, Full-Depth Teeth, and a Diametral Pitch of Unity in the Plane of Rotation Values of the Lewis)

Number of Teeth	Y	Number of Teeth	Y
12	0.245	28	0.353
13	0.261	30	0.359
14	0.277	34	0.371
15	0.290	38	0.384
16	0.296	43	0.397
17	0.303	50	0.409
18	0.309	60	0.422
19	0.314	75	0.435
20	0.322	100	0.447
21	0.328	150	0.460
22	0.331	300	0.472
24	0.337	400	0.480
26	0.346	Rack	0.485

Figure 1 Spur-gear geometry factors J. Source: The graph is from AGMA 218.01, which is consistent with tabular data from the current AGMA 908-B89

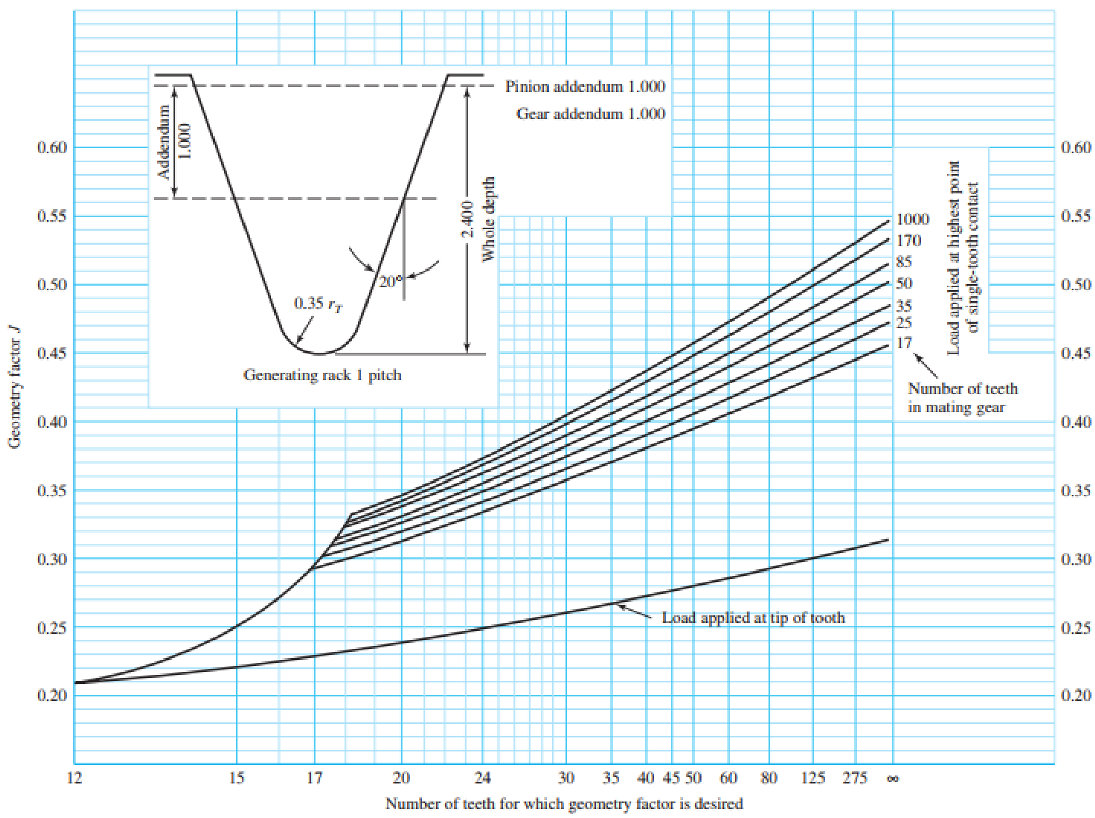

Figure 2 Dynamic factor Kv. (ANSI/AGMA 2001-D04, Annex A)

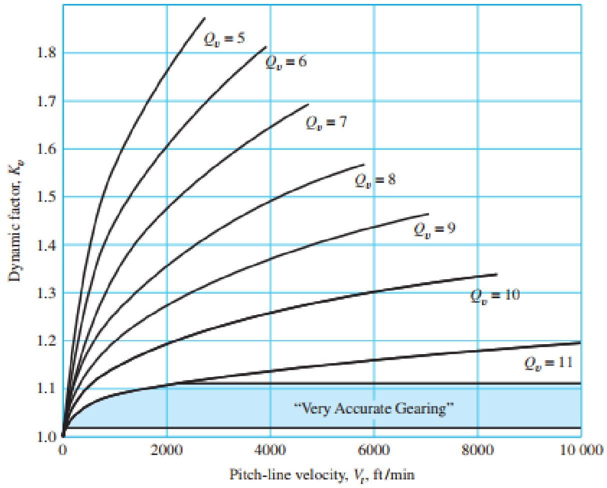

Figure 3 Pitting resistance stress-cycle factor ZN. (ANSI/AGMA 2001-D04.)

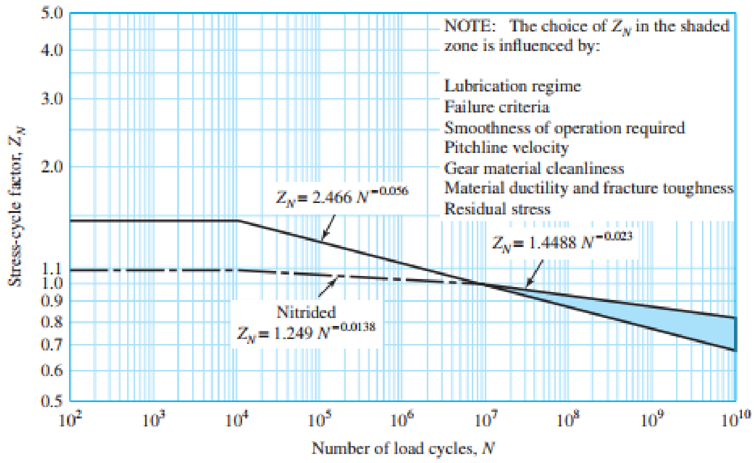

Figure 4 Other gear factors

Load Distribution Factors K_m

Face Width in	(mm)	K_m
<2	(50)	1.6
6	(150)	1.7
9	(250)	1.8
≥20	(500)	2.0

K_s — to account for size
K_s=1 unless teeth are very large

K_B — to account for gear with a rim and spokes
K_B=1 for solid gears

K_I — to account for extra loading on idler
K_I=1 for non-idlers, K_I=1.42 for idler gears

Driving Machine	Driven Machine: Uniform	Moderate Shock	Heavy Shock
Uniform (Electric motor, turbine)	1.00	1.25	1.75 or higher
Light Shock (Multicylinder engine)	1.25	1.50	2.00 or higher
Medium Shock (Single-cylinder engine)	1.50	1.75	2.25 or higher