Experimental Investigation Failure Analysis of Polyamide 66 Composite Spur Gear Subjected to Torque and Bending Loads

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Abstract: There are several benefits to using composite materials for gears made of Polyamide 66 (PA66) reinforced with Short Carbon Fibre (SCF). It includes lightweight construction, enhanced strength, noise reduction, and increased resistance to wear and corrosion. This study investigates the mechanical properties of PA66 composites with varying fiber contents, specifically examining the tensile, flexural, compression, and density of specimens. This study also investigates the manufacturing process of composite spur gears and employs analytical methodology to ensure design robustness under varying loads. The torque and the twisting angle of the spur gear have been evaluated using an analytical approach. An experimental approach was used to determine different types of torque are 37, 19, and 28 Nm, and the twisting angles are 8.5, 17, and 28 degrees respectively. Then the life of the composite gear pair was estimated at 2x10^9 cycles by analytical approach. Despite the failure of the parameters, the results were deemed to be satisfactory. Further, the analysis extends to the examination of failed gear teeth using Field Emission Scanning Electron Microscopy (FESEM). The knowledge acquired offers insightful recommendations on the durability and usability of composite gears under various operating circumstances. Their findings were corroborated through rigorous experimental assessments.

Keywords: Experimental Investigation; Failure Analysis; FESEM; Mechanical Testing; SCF/PA66 Composite Spur Gear; Torque and Bending Load

1. Introduction

Composite materials have emerged as a cornerstone in modern engineering, offering a paradigm change in material science by combining disparate properties to achieve superior performance[1,2)]. In the realm of mechanical systems, the integration of composites, particularly in gear manufacturing, is a compelling avenue for innovation. Composite spur gears, in particular, have garnered attention because of their potential to redefine the traditional trade-offs among strength, weight, and durability[3)]. An experimental failure analysis of composite spur gears is crucial for deciphering the intricate mechanisms governing their performance under diverse operational conditions. In the model that is described, the changing load acting on gear with addendum variations is considered[4)]. Because addendum adjustments alter resistance characteristics and structural variables, choosing the right one is essential. The module constitutes one of the most important spur gear factors; an increased module suggests a higher level of dynamic stress[5)]. More favorable results are achieved when the gear tooth geometry is tweaked[6)]. The load at contact during gear, tooth engagement is not constant; rather, it fluctuates due to irregularities in the meshing of the gear teeth, a change in mesh during the movement, and variations in the tooth profile[7)]. Further, the integration of SCF with PA66, commonly referred to as nylon 66, represents a leading-edge development in modern materials science[8)]. This collaboration offers significant advantages over traditional materials by enhancing their mechanical properties while maintaining versatility in applications across various industries.

The fracture traits of the resin drastically weaken as a consequence of this hydrolysis[9)]. Failure and mechanical features Interfacial shear strength, fiber variation, and implantation conditions are considered while discussing behaviors[10)]. Scuffing on the gear tooth between the lowest point of single tooth contact (LPSTC) and the start of the

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active profile has been seen on the test gear under lubricated conditions. The most important predicted gear tooth heat in this area[11], and a research investigation involving two spur gears that underwent deliberate wear and pitting[12]. Employing a test environment, the damping characteristics of all three materials were examined[13]. One of the key aspects impacting a polymer's mechanical characteristics, interface contact scenarios, and, eventually, wear and fatigue phenomena is temperature[14]. The experiment's findings demonstrated that a single MoS_2 application may greatly enhance anti-wear abilities at lower speeds[15]. Anisotropic elasticity served as a framework for the FEM determination of fracture mechanics factors[16]. Pitting on the edges of gear teeth is among the main causes why power transmissions fail[17]. The findings for machine-cut acetal gears are expected to be contrasted with earlier released data on injection-molded polymer gears[18]. Twin-disc topologies can be employed to simulate the rolling-to-sliding transition around this tooth position, which enormously affects the life span of polymer gear drives[19]. For structural and abrasive wear instances, polymer matrix composites' wear properties have to be examined and optimized, carbon fibers and Al_2O_3 were mixed to create composites, with Polyamide 6 serving as the basis material[20,21]. The accuracy of the processes has also been validated by comparison between the existing numerical and experimental findings in the literature[22].

Using a power absorption type gear test system, the performance of the infusion molded polyamide 6 and polymer nano-composite gears was examined at various torque levels[23]. Composite gears are the superior option for metallic gears because they exhibit more power than steel alloys[24]. Polymer gears often fail due to a pair of causes, as demonstrated by testing: fatigue and unexplained melting[25]. An innovative method for forecasting the transient operating temperature of a gear pair made of polymer and steel when operating under load has been proposed[26,27]. Medium-strength and lightest gears are crucial for the robotics & toy industries[28]. By determining and comparing the breakdown strength, and wear coefficient of friction for the materials under investigation, improved polymer gear designs were made possible[29]. Nowadays, the rule is generally agreed upon that high-speed machining is one of the essential production technologies for achieving high productivity and throughput[30]. The gear tooth profile may alter from its initial dimensions and configuration when subjected to time-varying loads and when debris is introduced, when friction and wear cause the gear to overheat, as well as when other nonlinear factors like backlash lead the gear to overheat[31]. By addendum and percentage SCF and PA66 variation coefficient in spur gear are steps from lower to higher positive value[32]. CF and PA66 are widely used to manufacture the parts for sports, automobiles, defense, and construction due to their lighter weight, higher mechanical strength, less noise, and higher specific stiffness and strength[33-35]. To modify an existing gear box that was originally coupled to an engine so that it can now be mechanically coupled to a DC motor, especially when considering the use of magnetic gears[36,37]. In Mechanical and thermal conductivity, reinforcing confirms the study's relevance and dependability in directing the development of innovative materials for sectors including automotive, sports, and aerospace[38].

The SCF and PA 66 composite material has been used for specimens and gear preparation. Because of it's unique, superior qualities and versatility, reinforced composite materials are increasingly used instead of conventional materials. Tensile, flexural, and compression specimen failure analysis is rigorously done to get the mechanical properties. SCF in PA66 can be used alongside a varied range from 00 to 60%, to determine the optimal mechanical properties tailored to the gear application.

2. Material and fabrication processes

2.1. Materials: short carbon fiber and Polyamide 66

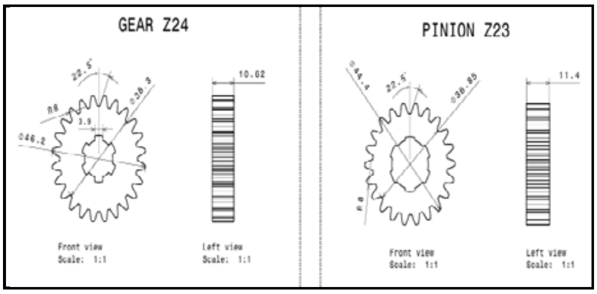
SCF as shown in Figure 1(b) is also available in braided form, with a 6 µm diameter and a length of 6 mm, offering flexibility for a range of applications. The most popular thermoplastic substance, PA66, is recognized for its remarkable strength and resistance to heat. It is the material of choice for machine part production because of its high melting point and exceptional abrasion resistance. Making room for handling and processing convenience, these pellets have an average diameter of 1.5 mm and a length of 2 mm[2], as shown in Figure 1(a).

2.2. Composite spur gears design procedure

Design software is used to create spur gear models, which ensure that geometrical dimensions match the established requirements and geometry of vehicle two-wheeler gearboxes. The composite spur gears design procedure are to collect the input data, material selection, number of teeth, face width, module, pressure angle, gear type, and PCD. Open the CAD software and create a new part. Draw the

(a) SCF (b) PA 66

Fig. 1: Materials: (a) SCF, (b) PA66[2]



(a) Pinion (b) Gear

Fig. 2: Pinion and Gear Dimensions

PCD, create a single tooth profile, and pattern the tooth. To extrude the gear, add details-Keyway or hub, chamfer/Fillet, mounting holes, web design, lightning holes, assembly, and motion check. Figure 2(a) and 2(b) display the spur Pinion and Gear dimensions, respectively.

2.3. Spur Gears Manufacturing

To create tensile and density test specimens, rectangular plates were initially developed and subsequently cut into sizes that complied with ASTM D-792 and ASTM D-638-14requirements.

A mixture of PA66 and SCF materials was fed into a feeding unit's single excluder for three minutes at a speed of 100 rpm. Melted plastic is propelled via a nozzle by the plunger, which also acts as a runner and gate system to allow the plastic to enter the mold cavity. To harden the specimen, the fluid was then put into a mold and cooled for seven seconds[27)]. The injection molding parameters of specimens as shown in Table 1. The composite spur gear and tensile specimen manufacturing procedure as shown in Figure 3.

Table 1: Injection Molding parameters of specimens

Parameter	40%SCF/PA66
Speed of Injection (rpm)	65
Pressure of Injection (Bar)	40
Time for Cooling (sec)	25
Temperature of Nozzle (^{0}C)	285-320
Temperature of Mold (^{0}C)	80
Keeping Time(sec)	8

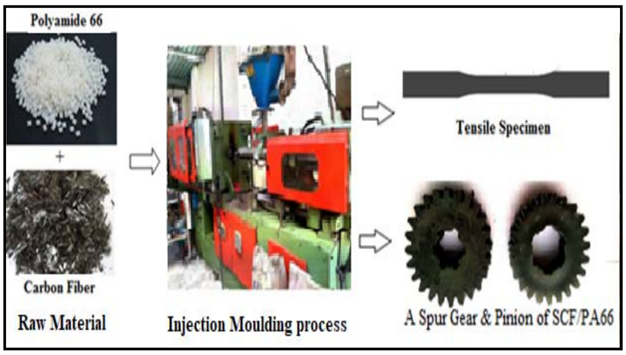
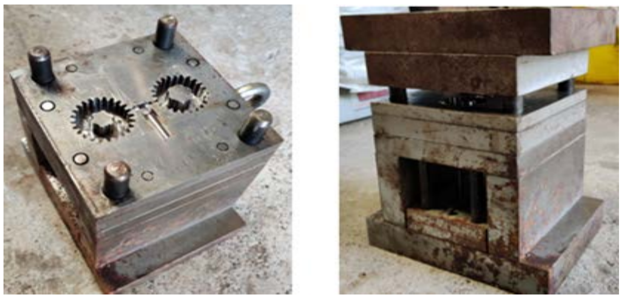


Fig. 3: Composite Spur Gear and Tensile Specimen Manufacturing Procedure[27)]



(a) Mold Half Cavity (b) Mold Complete Assembly

Fig. 4: (a) Half Cavity, (b) Complete Assembly-Mold [27]

2.4. Manufacture of Spur Gears Mold

Initially, specialized software was employed to model and design every mold component. The dimensions, appearances, mechanical characteristics, cylinder temperature, injection speed, and mold temperature are only a few parameters that are carefully considered when creating a mold. For corrosion resistance, superior surface finish, and reinforced polymers, martensitic stainless steels 420C and 440C are used in moulds.The spur gear mold assembly is made up of the following parts: spacer, sprue bush, cavity plate, ejector plate, ejector back plate,core back plate, core plate-1, core plate-2, ejector plate, and top plate. The runner and gates were then routed the composite material in molten form via a sprue and into the cavities. Using the ejector pin to push the ejector plate, the component is extracted once the mold has cooled27). The half-cavity mold is shown in Figure 4(a), and the mold assembly is shown in Figure 4(b).

3. Design & Fabrication of Spur Gear Fixture

In the realm of mechanical engineering and precision manufacturing, ensuring the reliability and performance of spur gears is of paramount importance across diverse mechanical systems. These gear components, valued for their simplicity and effectiveness in power transmission, find wide applications, from automotive transmissions to industrial machinery. To uphold the quality and functionality of spur gears to meet rigorous industry standards, the utilization of a specialized tool known as a "Spur Gear Testing Fixture" is indispensable. Computer-Aided Three-Dimensional Interactive Application (CATIA), renowned and robust computer-aided design (CAD) software, assumes a pivotal role in the development of this fixture. A 3D view of the Gear testing fixture is shown in Figure5.

It replicates the real-world operating conditions, scrutinizes the mechanical properties of spur gears, and verifies their suitability for specific applications. By harnessing CATIA's versatile design capabilities of CATIA, engineers and manufacturers can craft a testing fixture precisely tailored to their requirements, ensuring

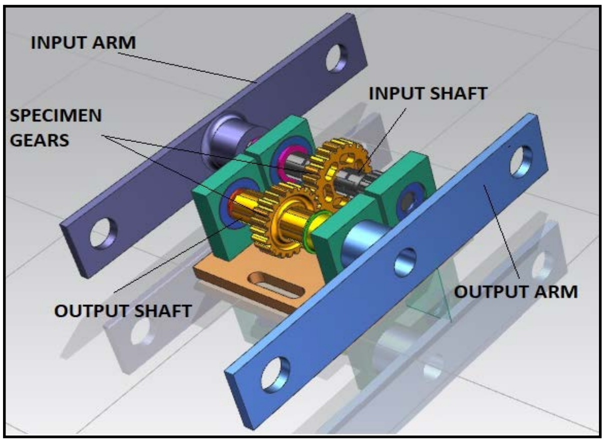


Fig. 5: Gear Testing Fixture in Three-Dimensional View

gear compliance with the most effective quality and performance standards. The primary objective of a Spur Gear Testing Fixture is to subject the spur gears to meticulously controlled and systematic assessments.

4. Analytical Approach of Composite Spur Gear

The analytical approach strengthens our understanding of this phenomenon. By using the parameters, calculated such as Tangential load, Bending Strength, Wear Strength, and Dynamic load and determine the factor of safety also. Further, the torque, angle of twist, and life of the composite spur gear pair were calculated.

4.1. Calculation of Torque and Angle of Twist of Composite Spur Gear

The formulae of tangential load, bending strength, wear strength, and dynamic load are considered for the calculation purpose of spur gear force analysis[38].

$$Ft = \frac{Pd}{Vp} \quad (1)$$

$$F_B = \gamma \ x \ \sigma_b \ x \ b \ x \ Pc \quad (2)$$

$$F_w = dp \ x \ b \ x \ Q \ x \ K \quad (3)$$

$$Fd = F_T + \left[\frac{0.164 \text{ x } Vp\ (cb+Ft)}{0.164 \text{ x } Vp + 1.485\sqrt{cb+Ft}}\right] \quad (4)$$

$$Cv = (3+Vp)/3 \quad (5)$$

The calculations of gear forces analysis for 40%SCF/PA66 are given below:
Ka = 1.25
Km = 1.5
T= 1425 N-mm
P_d = 211.713 W
N_p& N_g1135 &1088 rpm respectively.
V_p = 2.419 m/s
C_v = 1.8063 m/s

Table 2: An Analytical Approach Result Table for Different Tests

Sr. No.	Parameters	Values for 1st Test	Values for 2nd Test	Values for 3rd Test
1	Tangential load, F_t (N)	170.436	87.520	128.978
2	Bending Strength, F_B (N)	692.424	692.424	692.424
3	Wear Strength, F_w (N)	589.921	589.921	589.921
4	Dynamic load, F_d,(N)	193.222	110.306	151.764

The results of forces analysis of spur gear pair for 40%SCF/PA66 by Analytical Approach as presented in Table 2.
Hence, the pinion design is safe under the condition of beam strength, wear strength, and dynamic load of 40% SCF/PA66 composite spur gears.

4.2. Life of the Composite Spur Gear

By using the Torsional Equation calculate 'θ'
Shaft length=155 mm.
$\theta = TL/GJ$
E=2G(1+υ)
J= 261791.3521 mm4
Put the above values in the Torsional Equation No. 6
θ= 16.83°
Number of Life Cycles of composite gear

$$\sigma_{max} = \frac{M}{I} Y$$

$$Y_p = 0.154 - \frac{0.912}{23} = 0.1143 (9)$$

σ_{max} = 13.92 MPa

$$log(N_f) = -m \times log(\sigma_{max}) + C (10)$$

m = 0.1 , c = 9.25

$$log(N_f) = -0.1 \times log(13.92) + 9.25$$

$$(N_f) = 10^{9.13544}$$

$N_f = 1.32x10^9$ cycles

5. Experimental Approach of Composite Spur Gear

In the experimental investigation of the composite spur gear performance, meticulous attention was ready to assembling and mounting the gear pair onto a precision fixture. This fixture provided a stable platform, minimized extraneous variables, and ensured a reliable analysis. Before experimentation, thorough calculations were conducted to determine the key output parameters, including the torque and twist angle. The experimental results provided invaluable insights into the performance characteristics of the gear pair. This holistic approach facilitates a deeper understanding of gear dynamics and enables optimization of gear design for enhanced

Fig. 6: Test Rig for Gear Pair

durability and performance. By comparing experimental data with theoretical predictions, disparities were identified, leading to refined design methodologies and improved gear performance in practical applications.

5.1. Experimental Test Setup

The comprehensive evaluation setup, featuring cutting-edge instrumentation and rigorous safety protocols, was designed to assess the precise angle control capabilities of the 11.3 KN-m rotary actuator. The actuator's efficiency and effectiveness under varied working conditions could be monitored and assessed in real-time. The sensors and sophisticated data-collecting devices are installed in the setup. The implementation of safety protocols in the configuration defines the safety of workers and equipment, thereby validating its appropriateness for assessing the actuator's operational characteristics plus its suitability for a variety of industrial uses necessitating accurate torque measurement. Overall, the comprehensive test setup provides invaluable insights into the operational behavior and performance efficiency of the rotary actuator, enabling informed decisions for its use in industrial applications as shown in Figure 6.

5.2. Specification of Test Setup

Application: Evaluation of static torsional moment of a rotary actuator
Capacity: 11.3 KN-m
Operating Software: MTS Software
Hydraulic System: Provided by MTS
Input Parameters: Torque, Twisting Angle
Software Functionalities:
Manual Commands: For precise control
Graphical Visualization: For data analysis
Manager Tab: For overall system management
Starting Angle: 0.565 degrees
Purpose: Thorough testing and validation of military-grade pumps manufactured by MTS, meeting stringent quality standards.

5.3. Static Experimental Spur Gear Results

The results of the static experimental tests provide invaluable information about the mechanical behavior and performance of the subject component when subjected to controlled conditions. By carefully monitoring and documenting the data, these findings enable a comprehensive understanding of the component's response to various levels of applied force or torque. This knowledge serves as a crucial foundation for a detailed analysis of the results, emphasizing their importance in guiding design choices, optimizing performance, and ensuring the component's suitability for its intended use.
These findings suggest a decrease in torque tolerance with an increase in the angle of twist, indicating potential vulnerabilities in the gear's resilience. Notably, the experiment only considered static loads, while real-world gears are exposed to dynamic forces that can significantly influence their failure point. Additional investigation, incorporating dynamic loading, is necessary to determine a safe operating torque for practical applications. The static experimental spur gear results as shown in Table 3.

5.4. Composite Spur Gear Failure Mode

The evidence indicates that the gear tooth did not fail at the initial stage but fractured at a specific torque and twisting angle, as shown by the absence of early cracks and the sudden brittle breakage observed at the tooth root. The material, 40% SCF/PA66, is inherently brittle, and the fracture originated from the root where maximum stress accumulates under load. The failure pattern, including clean, jagged surfaces and fiber pull-out, confirms that breakage occurred only after the applied torque exceeded the material's threshold. This highlights the importance of understanding torque-induced stress in brittle composites and reinforces the need for precise analysis in scientific research. The composite spur gear failure from its root as shown in Figure 7.

Table 3: Static Experimental Spur Gear Results

Sr. No	Static Torsion Test Description	Observations
1	Angle at the start (^{0}C)	0
2	Null Torque at the Start (Nm)	8.2
3	Angle at First Teeth Pair Breakage (^{0}C)	8.5
4	Torque at First Teeth Pair Breakage (Nm)	37
5	Angle at Second Teeth Pair Breakage (^{0}C)	17
6	Torque at Second Teeth Pair Breakage (Nm)	19
7	Angle at Third Teeth Pair Breakage (^{0}C)	28
8	Torque at Third Teeth Pair Breakage (Nm)	28
9	Visual Observation	Brittle Failure of Teeth

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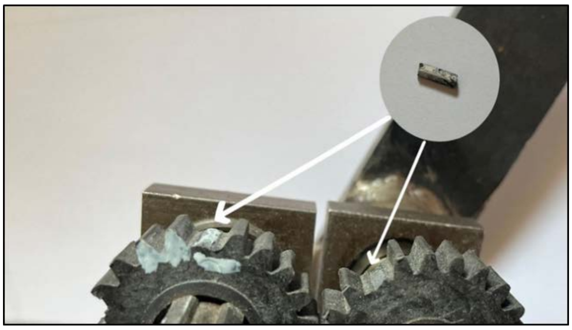


Fig. 7: Composite Spur Gear Failure from Root

6. FESEM Analysis of Composite Gear Teeth: Unveiling Structural Insights

FESEM serves as a highly effective tool for examining the microstructural details and surface characteristics of composite materials. In this study, FESEM analysis on a sample of composite gear teeth to explain its structural makeup, fiber distribution, and surface morphology. These gear teeth, manufactured using advanced polymer matrices reinforced with high-performance fibers, underwent meticulous examination to uncover manufacturing quality, interfacial bonding, and potential wear mechanisms. Through high-resolution imaging and elemental analysis, our research provides insight into critical features that are indispensable for comprehending the performance and durability of composite gear systems. Gear failure findings not only advance the understanding of composite materials in gear applications but also offer valuable recommendations for optimizing gear design and performance across a variety of industrial sectors.

6.1. Test Setup and its Specification

The test setup comprises an FESEM, and high-resolution images of the sample's morphology are obtained by the FESEM through the use of an electron beam that is focused and scanned across the sample's surface using a field emission cathode. The FESEM is the FEI Nova Nano SEM 450, which has in-lens TLD, SE, and BSE detection capabilities and a resolution of 1.0 nm at 15 kV, 1.4 nm at 1 kV, and 1.8 nm at 3 kV and 30 Pa. Conversely, the elemental detector used is the Bruker X Flash 6|30, which is renowned for its remarkable energy resolution (123 eV at Mn Ka and 45 eV at C Ka). This machine has various applications, such as surface morphology examinations, elemental analysis, both qualitative and quantitative, and assessment of microscopic features. The FESEM testing Machine is shown in Figure 8.

6.2. Key Findings from FESEM Analysis

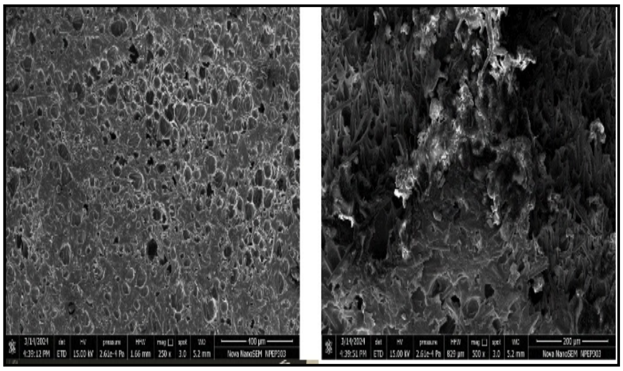
Fiber Distribution, Interfacial Bonding, Surface Roughness, Detected Defects or Anomalies. FESEM analysis at 250X magnification meticulously examines SCF- SCF-reinforced PA66 composites, revealing fiber distribution, interface characteristics, and defects. At 500X

Fig. 8: FESEM Testing Machine

magnification, FESEM testing scrutinizes finer details such as fiber morphology and interfacial bonding, guiding the refinement of composite design for enhanced mechanical properties in diverse industrial applications. The images of 250X and 500X magnification factors are as illustrated in Figure 9 (a) and 9 (b), respectively.

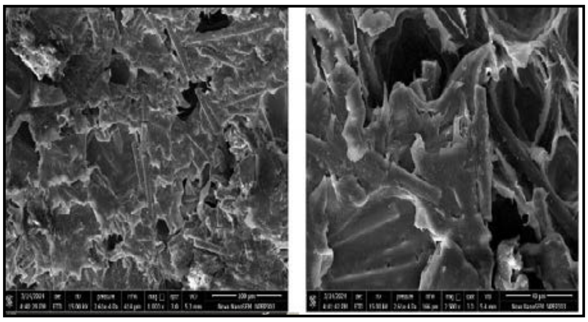
At 1000X magnification, FESEM tests reveal intricate details of SCF-reinforced PA66 composites, including fiber orientation, dispersion, and interface bonding variations. This level of scrutiny aids in identifying optimal formulations and fabrication techniques to enhance mechanical properties across applications. Scaling up to 2500X magnification, FESEM analysis provides unparalleled insights into the nano-scale features of SCF-reinforced PA66 composites. This resolution allows for precise visualization of individual fiber structures, detection of nano-scale defects, and assessment of composite matrix homogeneity. The images of 1000X and 2500X magnification factors as illustrated in Figure 10(a) and 10(b), respectively.

At 5000X magnification, FESEM testing offers a detailed view of SCF-reinforced PA66 composite microstructures, facilitating the examination of fiber-matrix interactions, filler distribution, and nano-sized features. This resolution enables thorough assessment and optimization of



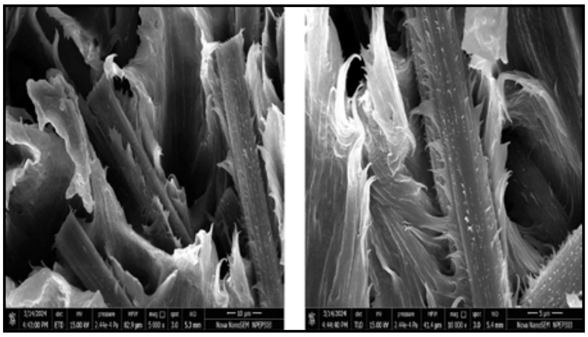
(a) (b)

Fig. 9: (a) 250X and (b) 500X Magnification Factor



(a) (b)

Fig. 10: (a) 1000X and (b) 2500X Magnification Factor



(a) (b)

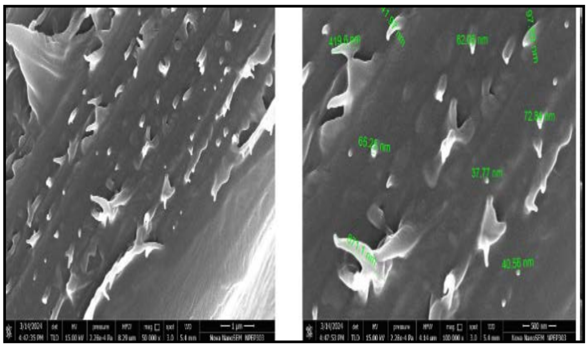
Fig. 11: (a) 5000X and (b) 10000X Magnification Factor

composite properties for diverse industrial applications. Scaling up to 10000X magnification, FESEM analysis provides unprecedented insights into the nano-scale morphology of SCF-reinforced PA66 composites. This level of scrutiny reveals ultrafine structural details, guiding manufacturing processes and material property tailoring for superior mechanical performance in demanding engineering environments. The images show the 5000X and 10000X magnification factors as shown in Figure 11 (a) and 11 (b), respectively.

At a magnification of 50,000X, FESEM testing provides detailed insights into the nanostructures of SCF-reinforced PA66 composites, allowing for a thorough analysis of fiber morphology and matrix characteristics. This information is invaluable for optimizing processing parameters and enhancing mechanical properties in various industries, such as aerospace and automotive. With a magnification of 100,000x, FESEM offers unparalleled clarity, enabling precise measurements of nano-scale dimensions as presented in Figure 12(a) and (b) respectively. This level of scrutiny allows researchers to fine-tune material properties with a high degree of accuracy, ultimately important to the development of high-performance PA/SCF materials for advanced engineering applications.

6.3. Dimension Measurement (Hair Structure) of SCF

During the FESEM test, the different nano-fiber diameter hair-like structures of the composite failure spur gear were found. The size of the hair-like structures, which are likely



(a) (b)

Fig. 12: (a) 50000X and (b) 100000X Magnification Factor

Table 4: Diameters of the Hair-Like Structure of Composite Materials

SCF/PA66	Diameter in (nm)	Average Diameter (nm)
40%	37.05	189.7688
	40.56	
	41.97	
	62.05	
	65.25	
	72.84	
	97.50	
	419.6	
	871.1	

nano-fibers, shows significant variation. The minimum diameter recorded is 37.05 nm, while the maximum diameter recorded is 871.1 nm. The average diameter for all the nano-fibers is 189.7688 nm. The diameters of the hair-like structure of the composite failure composite gear as shown in Table 4.

7. Results and Discussion

The study presents findings on the performance of composite spur gears achieved through an analytical approach, employing a combination of short carbon fiber and polyamide 66.

7.1. Forces Analysis of Composite Spur Gear

The comprehensive force analysis results underscore the robustness and reliability of the 40% SCF/PA66 composite spur gear under various operational scenarios. With a meticulous examination of tangential loads, bending and wear strengths, as well as dynamic loads, the gear's performance across different stress factors is thoroughly evaluated. Notably, the consistency in bending and wear strengths throughout the tests highlights the material's resilience and suitability for demanding applications.

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Furthermore, the calculated factors of safety provide assurance of the gear's structural integrity and its ability to withstand operational stresses with ample margin. Additionally, the angle of twist in the shaft serves as a crucial parameter in assessing the gear's torsional behavior, further bolstering confidence in its performance under real-world conditions. The pinion design is safe under the condition of beam strength, wear strength, and dynamic load of 40% SCF/PA66 composite spur gears.

7.2. Analytical Approach of Composite Spur Gear

The estimated number of life cycles (N_f) serves as a pivotal metric, reflecting the durability and longevity of the composite spur gear system under operational conditions. By meticulously analyzing the maximum stress (σ_max) endured by the gear, approximately 13.92 MPa—derived from the applied torque (M = 6914.08 N-mm), a moment of inertia (I = 468387.05 mm^4), and Lewis's form factor (Yp = 0.1143), engineers gain valuable insights into its mechanical performance. Leveraging a logarithmic equation relating N_f to σ_max, with constants m = 0.1 and c = 9.25, reveals that the gear is expected to withstand approximately $N_f \approx 1.32 \times 109$ life cycles. This estimation underscores the gear's robustness and suitability for sustained usage in demanding industrial applications, facilitating informed decision-making regarding its design optimization and integration within mechanical systems.

7.3. Experimental Approach of Composite Spur Gear

The graph appears to show the stages of teeth breaking over a while, possibly during a torque test on a gear. On the y-axis, the number of fractured teeth is displayed, and on the x-axis, the time. The experimental results graph as shown in Figure 13. There are three distinct peaks, so it can analyze the results in three stages:

Stage 1: The graph shows a gradual increase in the number of broken teeth over time. This initial stage suggests that the weakest teeth are fracturing first, likely due to imperfections or manufacturing defects.

Stage 2: The graph exhibits a steeper rise in the number of broken teeth, reaching a distinct peak. This second stage represents a period of more frequent tooth breakage, possibly indicating a critical point of stress for the gear.

Stage 3: After the second peak, the graph shows a slower increase or plateau in the number of broken teeth. This final stage suggests that the gear is nearing complete failure. Compared with the analytical and experimental approach, approximately closer values are obtained.

7.4. FESEM Analysis of Composite Spur Gears

The results of the FESEM analysis unveiled critical insights into the microstructure and surface attributes of composite gear teeth. This analysis opens new avenues for creating high-performance composite gear materials tailored to meet the demands of cutting-edge engineering applications in various sectors. The findings from our FESEM analysis of composite gear teeth provide valuable insights into their microstructure and surface characteristics. By examining samples at magnifications factor ranging from 250X to 100,000X, were able to uncover critical details of gears failures.

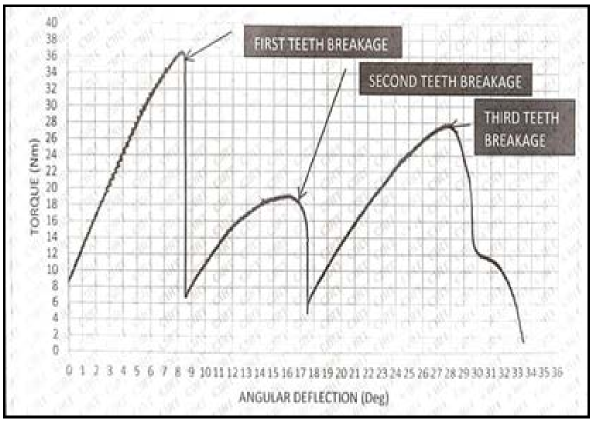

Fig. 13: Experimental Results Graph

8. Conclusion

Mechanical properties of SCF/PA66 of different blends are studied and 40% is found optimum value. By analytical approach, the tangential load, bending strength, wear strength, and dynamic load for different torque and twisting angles have been calculated. The life of the composite gear pair is 1.32x10^9 cycles estimated. By experimental approach, different types of torque are finding 37, 19, and 28 Nm and the twisting angles are 8.5, 17, and 28 degrees respectively. The maximum life of the composite gear pair is found for a minimum torque of 19 Nm acquired.

The torque test experiment provided invaluable insights into the process of gear tooth failure under increasing torque loads, revealing distinct phases of tooth breakage. The experimental results validated the accuracy of the analytical model by closely matching the experimentally obtained average breaking torque with the predicted value. To enhance gear design and manufacturing processes, future investigations should concentrate on analyzing material properties, examining individual tooth breakage torques, and employing microscopic techniques to identify failure modes. These gears failed at these parameters and showed good results.

The analysis incorporates a FESEM examination of the failed gear teeth, offering an in-depth understanding of the failure characteristics at the micro and nano scales. By analyzing the surface morphology and microstructure, FESEM provides essential insights into the physical and chemical interactions that contribute to gear failure. The microstructural information obtained from FESEM is vital

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for developing a comprehensive understanding of the performance and integrity of composite gear components under real-world operating conditions. This knowledge directly supports the optimization of gear design, manufacturing techniques, and material composition. Ultimately, this leads to the production of more reliable, efficient, and long-lasting composite gear systems.

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Nomenclature

Symbol	Description
F_t	Tangential Load (N)
Pd	Dynamic Load (N)
V_p	Pitch Line Velocity (m/s)
F_w	Wear Strength(N)
F_d	Dynamic load(N)
F_B	Bending Strength(N)
ϴ	Angle of Twist of the Spur Gear in degrees.
T	Torque **(**N-mm**)**.
J	Polar Moment of Inertia (mm^4)
υ	Poisson's ratio.
E	Modulus of Elasticity of the gear (MPa).
G	Modulus of rigidity of the gear (MPa).
L	Shaft's length (mm)
σ_{max}	Maximum Stress (MPa)
M	Bending Moment (N-mm)
N_f	Life (Number of cycles)

References

1) T. T. Petry, J. A. Kahraman, N. E. Anderson, and D. R. Chase, "Experimental Investigation of Spur Gear Efficiency," Journal of Mechanical Design, **130**(6) 62201-10 (2007). doi.org/10.1115/1.2898876
2) Dilip S. Choudhari and V. J. Kakhandki, "Characterization and Analysis of Mechanical Properties of Short Carbon Fiber Reinforced Polyamide66 Composites," EVERGREEN, **8**(4) 768-776(2021). doi.org/10.5109/4742120.
3) P. N. E. Naveen, M. Chaitanya Mayee, P. Gayathri, B. Kiran Goriparthi, and K. RaghuRam Mohan Reddy, "Design and optimization of nylon66 reinforced composite gears using genetic algorithm," Materials Today: Proceedings, Elsevier, **3**(4) 514–519 (2021). doi:10.1016/j.matpr.2020.10.694.
4) H. Ma, J. Zeng, R. Feng, X. Pang, and B. Wen, "An improved analytical method for mesh stiffness calculation of spur gears with tip relief," Mech Mach Theory, **98** 64–80 (2016). doi:10.1016/j.mechmachtheory.2015.11.01.7.
5) J. Kuria and J. Kihiu, "Effect of Gear Design Variables on the Dynamic Stress of Multistage Gears," **3**(2) (2012). Doi: 10.1016/j.jsv.2003.11.029
6) W. Li, A. Wood, R. Weidig, and K. Mao, "An investigation on the wear behavior of dissimilar polymer gear engagements," Wear, **271** (9-10) 2176–2183 (2011). doi: 10.1016/j.wear.2010.11.019.
7) V. Atanasiu and I. Doroftei, "Dynamic Contact Loads of Spur Gear Pairs with Addendum Modifications, " European Journal of Mechanical and Environmental Engineering, **49**(2) 27-32 (2008). Doi:10.1115/1.1564063#
8) Dilip. Choudhari and V. J. Kakhandki, "Comprehensive study and analysis of mechanical properties of chopped carbon fiber reinforced nylon 66 composite materials," Materials Today: Proceedings, Elsevier, **44**(6) 4596–4601 (2021). doi.org/10.1016/j.matpr.2020.10.828.
9) P. Y. Le Gac and B. Fayolle, "Impact of fillers (short glass fibers and rubber) on the hydrolysis-induced embrittlement of Polyamide 66," Composite B Engineering 153 256–263 (2018). doi: 10.1016/j.compositesb.2018.07.028.
10) Y. Ma, M. Ueda, T. Yokozeki, T. Sugahara, Y. Yang, and H. Hamada, "A comparative study of the mechanical properties and failure behavior of carbon fiber/epoxy and carbon fiber/polyamide 6 unidirectional composites," Composite Structure, **160** (89–99) (2017). doi: 10.1016/j.compstruct.2016.10.037.
11) B. Sarita and S. Senthilvelan, "Effects of lubricant on the surface durability of an injection molded polyamide 66 spur gear paired with a steel gear," Tribol International, **137** 193–211 (2019). doi: 10.1016/j.triboint.2019.02.050.
12) S. Raadnui, "Spur gear wear analysis as applied for tribological based predictive maintenance diagnostics," Wear **426** 1748–1760(2019). doi: 10.1016/j.wear.2018.12.088.
13) A. Sharma, M. L. Aggarwal, and L. Singh, "Experimental investigation into the effect of noise and damping using composite spur gear," in Materials Today: Proceedings, Elsevier, **4**(2) 2777–2782 (2017). doi: 10.1016/j.matpr.2017.02.156.
14) M. Kalin and A. Kupec, "The dominant effect of temperature on the fatigue behavior of polymer gears," Wear, **376** 1339–1346 (2017). doi: 10.1016/j.wear.2017.02.003.
15) F. Song, Q. Wang, and T. Wang, "Effects of glass

fiber and molybdenum disulfide on tribological behaviors and PV limit of chopped carbon fiber reinforced Polytetrafluoroethylene composites," Tribol International **104** 392–401 (2016). doi: 10.1016/j.triboint.2016.01.015.

16) K. Tanaka, K. Oharada, D. Yamada, and K. Shimizu, "Fatigue crack propagation in short-carbon-fiber reinforced plastics evaluated based on anisotropic fracture mechanics," International Journal Fatigue, **92** 415–425 (2016). doi: 10.1016/j.ijfatigue.2016.01.015.

17) G. Meneghetti, A. Terrin, and S. Giacometti, "A twin disc test rig for contact fatigue characterization of gear materials," in Procedia Structural Integrity, Elsevier, **2** 3185–3193 (2016). doi: 10.1016/j.prostr.2016.06.397.

18) K. Mao, W. Li, C. J. Hooke, and D. Walton, "Polymer gear surface thermal wear and its performance prediction," Tribology International, **43** (12) 433–439 (2010). doi: 10.1016/j.triboint.2009.07.006.

19) T. J. Hoskins, K. D. Dearn, Y. K. Chen, and S. N. Kukureka, "The wear of PEEK in rolling-sliding contact - Simulation of polymer gear applications," Wear, **309** (12)35–42 (2014). doi: 10.1016/j.wear.2013.09.014.

20) S. Swarup Mohanty, A. Kumar Rout, D. Kumar Jesthi, B. Chandra Routara, and R. Kumar Nayak, "Evaluation of mechanical and wear performance of glass/carbon fiber reinforced polymer hybrid composite," Materials Today Proceeding, **5**(9) 19854-19861 (2018).

21) Y. S. Kim, J. K. Kim, and E. S. Jeon, "Effect of the compounding conditions of polyamide 6, carbon fiber, and Al2O3 on the mechanical and thermal properties of the Composite Polymer," Materials, **12**(18) (2019). doi: 10.3390/ma12183047.

22) M. Ciavarella and G. Demelio, "Numerical methods for the optimization of specific sliding, stress concentration and fatigue life of gears," International Journal of Fatigue, **21**(5) 465-474 (1999). doi.org/10.1016/S0142-1123(98)00089-9.

23) S. Kirupasankar, C. Gurunathan, and R. Gnanamoorthy, "Transmission efficiency of polyamide nanocomposite spur gears," Material and Design, **39** 338–343 (2012). doi: 10.1016/j.matdes.2012.02.045.

24) P. B. Pawar and A. A. Utpat, "Analysis of Composite Material Spur Gear Under Static Loading Condition," in Materials Today: Proceedings, Elsevier, **2** (4-5) 2968–2974 (2015). doi: 10.1016/j.matpr.2015.07.278.

25) A. Pogacnik and J. Tavcar, "An accelerated multilevel test and design procedure for polymer gears," Material and Design, **65** 961–973 (2015). doi: 10.1016/j.matdes.2014.10.016.

26) S. M. Evans and P. S. Keogh, "Efficiency and running temperature of a polymer-steel spur gear pair from slip/roll ratio fundamentals," Tribology International, **97** 379–389 (2016). doi: 10.1016/j.triboint.2016.01.052.

27) Dilip S. Choudhari, V.J. Kakhandki, P.D. Malwe, H Panchal, D Mevada, "Investigation and performance analysis of short carbon fiber reinforced polyamide 66 of spur gears", International Journal on Interactive Design and Manufacturing, **18** 7115-7126 (2024). doi.org/10.1007/s12008-023-01303-x.

28) P. N. E. Naveen, M. Chaitanya Mayee, P. Gayathri, B. Kiran Goriparthi, and K. Raghu Ram Mohan Reddy, "Design and optimization of nylon 66 reinforced composite gears using genetic algorithm," Materials Today: Proceedings, Elsevier, **46** 514–519 (2021). doi: 10.1016/j.matpr.2020.10.694.

29) D. Zorko, I. Demšar, and J. Tavčar, "An investigation on the potential of bio-based Polymers for use in Polymer Gear Transmissions," Polymer Testing, **93** (2021). doi: 10.1016/j.polymertesting.2020.106994.

30) V. Krishnarajet, "Optimization of machining parameters at high-speed drilling of carbon fiber reinforced plastic (CFRP) laminates," Composite Part B Engineering, **43**(4) 1791–1799 (2012). doi: 10.1016/j.compositesb.2012.01.007.

31) Getachew A. Ambaye, H. G. Lemu, "Dynamic analysis of spur gear with backlash using ADAMS," Materials Today: Proceedings, Elsevier, 38 (5),2959–2967 (2020). doi: 10.1016/j.matpr.2020.09.309.

32) Dilip S. Choudhari, Vyasraj J. Kakhandki, Ganesh Iyer, "Optimization Performance Parameters Short Carbon Fiber Reinforced Polyamide66 Composite Spur Gear with Addendum Variation," Materials Today: Proceedings, **50**(5) 2084-2091 (2021). https://doi.org/10.1016/j.matpr.2021.09.419.

33) Rakesh Raushan, K.K. Dhande, N.I. Jamadar, Prateek D. Malwe, "Material characterization, design and analysis of CF/PA66 drive shaft with high strength carbon steel," Material Today Proceeding Elsevier, **64**(1) 51-58 (2022).doi.org/10.1016/j.matpr.2022.03.512

34) Rakesh Raushan, K.K. Dhande, N.I. Jamadar, "Modal Analysis of Carbon Fiber Reinforced Polyamide66 Drive shaft using Analytical and finite Element Approach," International Journal on Interactive Design and Manufacturing, (2024). doi.org/10.1007/s12008-024-01854-7

35) Rakesh Raushan, K.K. Dhande, N.I. Jamadar," Mathematical Modelling for Failure Analysis Composite Drive Shaft using Modal Flexibility and Curvature Method," Communication on Applied

Nonlinear Analysis, **3** (1) 42-55 (2024). https://doi.org/10.52783/cana.v31.555

36) Shailendra Singh Chauhan, Kanika Lamba, Diwakar Yagyasen, “Methods of Implementation in an Electric Vehicle Conversion and Vehicle Controller: A Review,” EVERGREEN, **11**(01) 156-177 (2024). doi.org/10.5109/7172252.

37) Kafi Hannan Alhadi, Agus Sigit Pramono, “Experimental and Numerical Test of Radial Internal Magnetic Spur Gear,” EVERGREEN, **11**(3) 2248-2256(2024). doi.org/10.5109/7236867.

38) Gh Owais Shah, Gaurav Arora, “Analyzing Thermal Conductivity of Composites through Different Theoretical Frameworks”, EVERGREEN, **11**(03) 1740-1752 (2024). doi.org/10.5109/7236826

Cite: D. Choudhari et al., "Experimental Investigation Failure Analysis of Polyamide 66 Composite Spur Gear Subjected to Torque and Bending Loads". Evergreen, 12 (03) 1501-1511 (2025). https://doi.org/10.5109/7388844.