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# Design and Computational Analysis of Hybrid Carbon Fiber-Enhanced Metal Matrix Composite Spur Gears

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**_Abstract_**

*The automobile industry has to find the alternative solution for steel grade gears to overcome the weight to high strength ratio and thermal consideration with high damping properties. This study describes the design, FEM analysis, and performance evaluation of three new hybrid composite spur gears: a monolithic carbon fiber/epoxy (80/20 weight percent) composite (A), and two hybrids with steel (B) and aluminum (C) matrices (64% CF, 21% Epoxy, 15% metal). Composite A, with a density of 1710 kg/m³, achieved a superior yield strength of 1096 MPa and a Young's modulus of 323 GPa using Taguchi optimization. Finite Element Analysis (FEA) evaluated theoretical models under a static load of 303.75 N and found that all composites superior to SCM420 steel by significantly. Composite A showed a 38.2% reduction in deformation (0.00134 mm as opposed to steel's 0.00217 mm) while maintaining a controllable von Mises stress of 45.06 MPa. Composite A's specific stiffness (E/ρ) was roughly 5.8 times higher than steel's. Strong agreement in deformation trends is found in a comparative analysis with recent literature on fiber-reinforced gears; however, the unique contribution of our metal-matrix hybridization approach in customizing stress distribution is also highlighted. With FEA results offering a high-confidence predictive model for future manufacturing, this work unequivocally shows that carbon fiber composites, especially the monolithic design, offer a revolutionary solution for lightweight, high-stiffness automotive gearing.*

**Keywords:** Composite gear, optimization, reinforcement, static analysis, taguchi method

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## INTRODUCTION

Gears are a key component in many machines and devices, transferring power and motion between spinning shafts [2, 4, 8, 12–14]. Due to their superior mechanical qualities, composite materials have supplanted traditional metals in gear design [1, 2, 6]. The strength-to-weight ratio of spur gears in automobiles increases the overall weight of the transmission gearbox [3].

Figure 1 gives the detailed information about the dismantled view of each and every small component and its identification to imagine that the position of each component in the gearbox of automobile system.

 

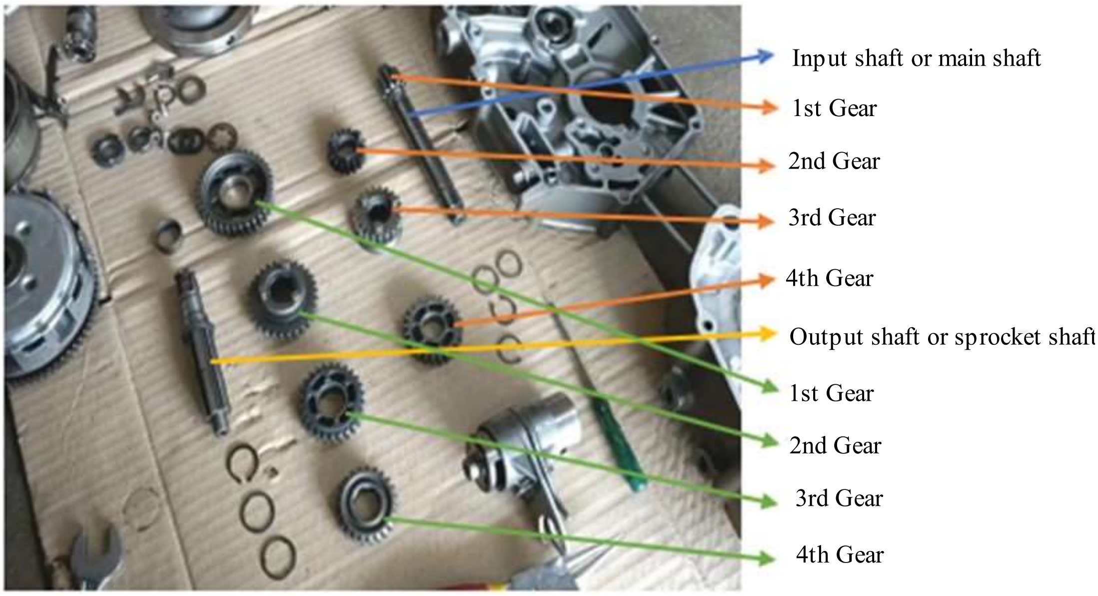


**Figure 1.** Gearbox dismantle view showing individual components.

Steel gears have a shorter work life, lower wear resistance, and lower vibration bearing ability [6–8, 24, 25]. Because of its poor strength, it has a shorter lifespan and lower efficiency. This is a crucial challenge in the vehicle industry. As a result, adding composite materials gear can overcome this problem [17, 21, 22, 23].

Gears can be created utilizing a variety of manufacturing procedures such as hobbing, casting, and indexing, with the life of the spur gear being a crucial consideration when adding composite materials [8].

The primary goal of this research is to improve strength and other mechanical qualities. The selection of composite materials is critical. There are numerous ways of composite manufacturing, such as stacking, reinforcing, and casting. The arduous process is theoretical computation of the mechanical properties of the composite material which are commonly benchmarked against standardized testing procedures [26]. It is possible to reduce the weight of the spur gear, resulting in an overall reduction of the vehicle's gear box [4].

## METHODOLOGY

The following steps are used to create the composite material spur gear with the best mechanical qualities achievable.

Carbon Fiber is the greatest choice for replacing existing materials such as different steel grades [18]. To boost the strength and ductility of the gear metal matrix reinforcement, the stacking manufacturing technique was used [10]. A composite material is one that is made from two or more constituent materials. These constituent materials have noticeably diverse chemical or physical properties, which are combined to form a material having qualities distinct from the separate elements [16, 20]. The main advantage of composite materials is their strength, rigidity, and lightness [6, 7]. Manufacturers are able to create qualities that precisely match the specifications for a specific structure for a specific purpose [6] by selecting the right mix of reinforcement and matrix material [5, 9]. In order to determine which material combination is best for manufacturing, CF reinforcing using SS and aluminum is carried out in this paper. Numerous industries, including automotive, aerospace, and aviation, use aluminum MMC due to their favorable strength-to-weight ratio and controllable deformation behavior, as demonstrated in recent numerical and experimental studies on AA1050 alloys [11, 19, 27, 28].

 

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For ease of installation and replacement of the current gear in the automotive gearbox, design characteristics such as face with diameter and thickness of the gear in accordance with pitting or wearing considerations as well as gear failure in bending are taken into account [5]. Validatory data for the designed composite will be obtained by FEM analysis [15].

## Data Set for Young's Modulus Using Taguchi Optimization

The Figure 2 shows that the composition's Young's modulus increases as the composition's CF% volume increases. Thus, 80% CF and 20% Resin are chosen for additional manufacture and testing by choosing the best design. Similarly other mechanical properties like Shear Modulus, Yield Strength, Density, and Poisson's ratio were calculated using the Taguchi optimization technique.

Table 1. Presents the standard mechanical properties of steel, carbon fiber, epoxy resin, stainless steel, and aluminum.

Table 1 shows the standard mechanical properties which were used to calculate composite materials mechanical properties by using conventional formulas to determine the optimal composition of composite materials and their mechanical properties,

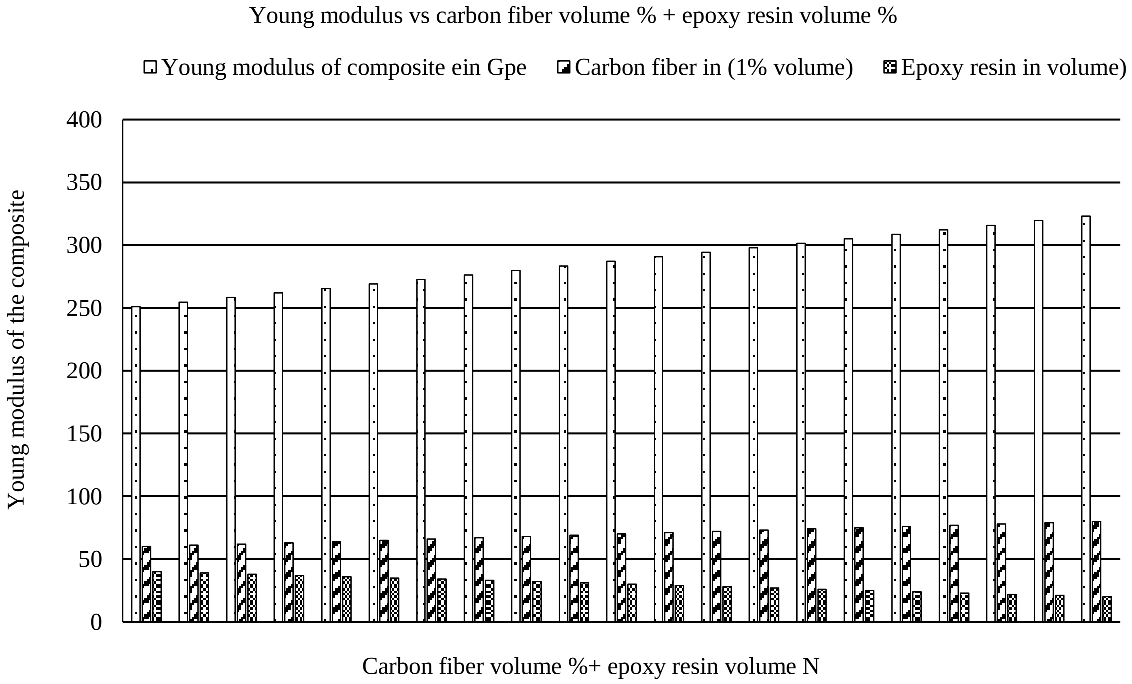


**Figure 2.** Young's modulus of composite A.

**Table 1.** Mechanical properties of pure materials [29].

| Materials name | Mechanical properties | | | | |
|---|---|---|---|---|---|
| | ***Young modulus (E) in GPa*** | ***Shear modulus (G) in GPa*** | ***Yield Strength (YS) in MPa*** | ***Material density (ρ) in Kg/m³*** | ***Poisson ratio (μ)*** |
| Steel SCM 420H | 200 | 80 | 365 | 7850 | 0.29 |
| Carbon Fiber | 395 | 8 | 1230 | 1800 | 0.2 |
| Epoxy Resin | 35.2 | 3.2 | 563 | 1350 | 0.35 |
| Steel metal matrix (SS 304) | 193 | 77 | 215 | 8000 | 0.29 |
| Aluminum metal matrix (AL 1050) | 71 | 26 | 124 | 2710 | 0.33 |

**Table 2.** Mechanical properties of composite materials [20].

| Composite | Young modulus E in GPa | Shear modulus G in GPa | Yield strength YS in MPa | Density ρ in Kg/m3 | Poisson ratio |
|---|---|---|---|---|---|
| A | 323.04 | 7.04 | 1096.06 | 1710 | 0.23 |
| B | 289.1 | 17.34 | 937.08 | 2635.5 | 0.245 |
| C | 270.842 | 9.692 | 924.03 | 1842 | 0.251 |

The spur gear design can be obtained by taking the Young's modulus, shear modulus, yield strength, and density from the preceding Table 2.

## Theoretical Design and Calculation

***Composite A – Carbon Fiber Mixed with Epoxy Resin***

Consider load (F) = 303.75 N, module (m) = 1.933, face width (b) = 10.6 mm, Lewis form factor (Y) = 0.337, tooth thickness (l) = 3.036 mm, Lewis height (h) = 2.358 mm. From Table 2, we have Young's modulus of composite A is (E) = 323.04 GPa.

Then, Bending stress (σb)Composite A on gear tooth

$$\sigma b = \frac{303.75}{1.933*10.6*0.337} = 43.989\ MPa \quad (1)$$

Deflection of the Composite A spur gear (δ)

$$\delta = \frac{16*303.75*2.358^3}{303.6*10^3*10.6*3.036^3} = 0.000708m \quad (2)$$

**Composite B – Carbon Fiber Mixed with Epoxy Resin and SS 316/SS 304 Metal Matrix**

Consider load (F) = 303.75 N, module (m) = 1.933, face width (b) = 10.6 mm, Lewis form factor (Y) = 0.337, tooth thickness (l) = 3.036 mm, Lewis height (h) = 2.358 mm. From table 2, we have Young's modulus of composite B is (E) = 289.1 GPa.

Bending stress (σb)Composite B on gear tooth

$$\sigma b = \frac{303.75}{1.933*10.6*0.337} = 43.989\ MPa. \quad (3)$$

Deflection of the Composite B spur gear (δ)

$$= \frac{16*303.75*2.358^3}{289.1*10^3*10.6*3.036^3} = 0.000734mm \quad (4)$$

**Composite C – Carbon Fiber Mixed with Epoxy Resin and AL 1050/AL 6082 Metal Matrix**

Consider load (F) = 303.75 N, module (m) = 1.933, face width (b) = 10.6 mm, Lewis form factor (Y) = 0.337, tooth thickness (l) = 3.036 mm, Lewis height (h) = 2.358 mm. From table 2, we have Young's modulus of composite C is (E) = 270.842 GPa.

Then, Bending stress (σb)Composite C on gear tooth

$$\sigma b = \frac{303.75}{1.933*10.6*0.337} = 43.989\ MPa. \quad .(5)$$

Deflection of the Composite C spur gear (δ) =

$$\delta = \frac{16*303.75*2.358^3}{270.84*10^3*10.6*3.036^3} = 0.000793mm \quad (6)$$

By Applying the basic formulas for the Thickness of layers is applied for the spur gear Face width and accordingly the layering sequence is decided. The innovative design – having fixed number of CF, Resin, and Metal Matrix with the help of stacking method – can be manufactured.

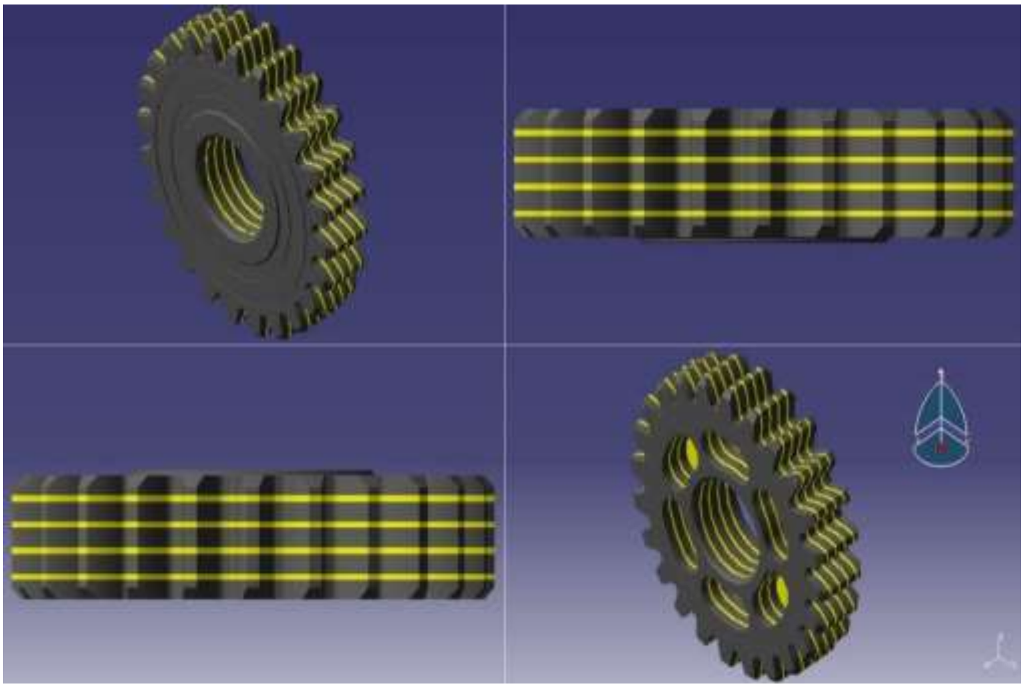

**Figure 3.** Composite A – production drawing of spur gear.

The information on the 80–20% composition of carbon fiber and epoxy resin is displayed in the Figure 3.

In the Figure 3 shows the gray color shows CF and Yellow color shows resin layer thickness arrangement.

Table 3 depicts the information about the detailed calculation and dimensions for the new designed composite spur gear in the different variants of the CF-Resin-SS/AL Grades.

**Table 3.** Design calculation of composite A, B, and C.

| | **Composite spur gear made up of 80% carbon fiber sheet and 20% epoxy resin (composite A)** | **Composite spur gear made up of 64% carbon fibre sheet, 21% epoxy resin & 15% steel 304 metal matrix (composite B)** | **Composite spur gear made up of 64% carbon fiber sheet, 21% epoxy resin & 15% aluminum 1050 metal matrix (composite C)** |
|---|---|---|---|
| Mass of carbon fibre | 49.52 gm | 61.05 gm | 42.63 gm |
| Mass of steel 304 metal matrix | | 14.31 gm | N.A. |
| Mass of Epoxy Resin | 12.38 gm | 20.03 gm | 14 gm |
| Single epoxy resin layer thickness | 0.36 mm | 0.26 mm | 0.26 mm |
| Single Steel 304 metal matrix diameter | NA | 0.5 mm | N.A. |
| Single Aluminium 1050 metal matrix diameter | NA | N.A. | 0.5 mm |
| Single carbon fiber sheet thickness | 1.71 mm | N.A. | 1.64 mm |
| Mass of Aluminium 1050 metal matrix | NA | N.A. | 10 gm |

 

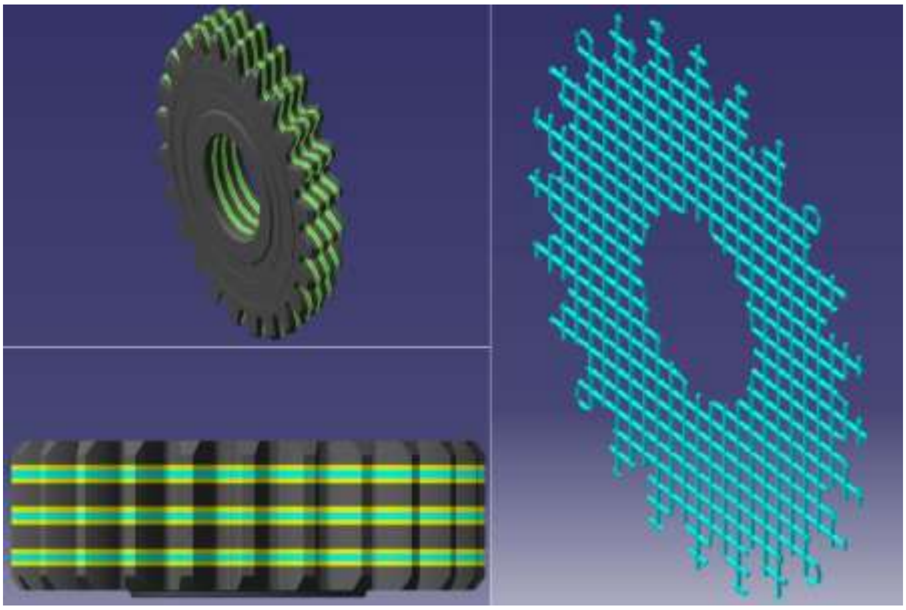

**Figure 4.** Composite B – production drawing of spur gear.

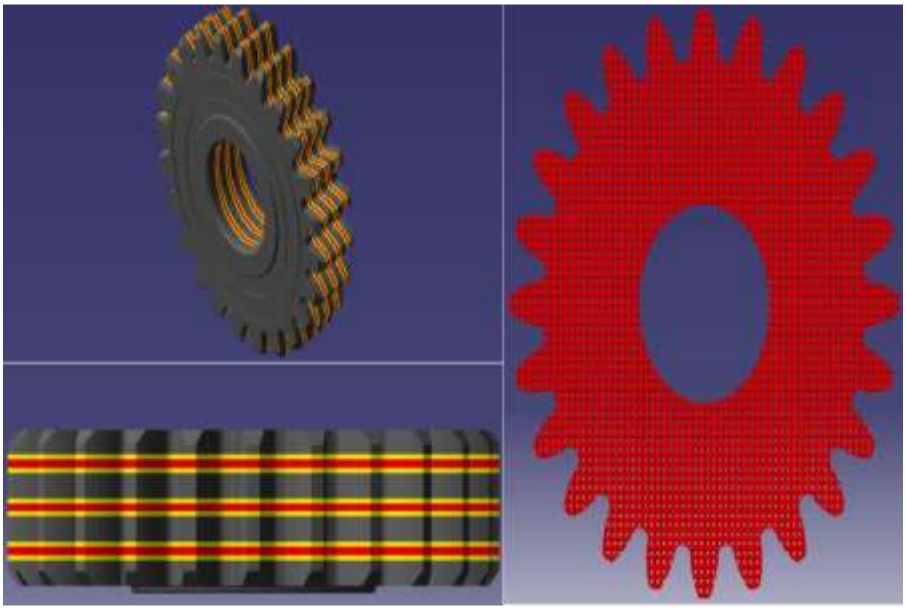

**Figure 5.** Composite C – production drawing of spur gear.

Figure 4 depicts the composite B Spur gear having 3 different materials Gray color indicates the CF, Blue color indicates the steel variants metal matrix and the yellow color shows the resin material. Figure gives exact idea about the composite layer design and production drawing.

Figure 5 depicts the composite C Spur gear having 3 different materials Gray color indicates the CF, Red color indicates the steel variants metal matrix and the yellow color shows the resin material. Figure gives exact idea about the layering sequence and manufacturing method.

## FEA ANALYSIS OF IDEAL AND COMPOSITE GEAR

### FEA Analysis of Ideal Gear

Figure 6 Ideal gear of steel material is having 35 teeth and 65 mm diameter which is traditionally used in the automobile gearbox and CAD file is along with meshing, mesh size is 1 mm. can be seen in the Figure 8.

 

Figure 7 shows boundary conditions were applied on spur gear blue color shows fixed position whereas red color show applied load which is 303.75 N.

Figure 8 depicts the maximum and minimum bending stress for conventional steel gear and Figure 9 shows the FEA results total deformations minimum and maximum values for the same.

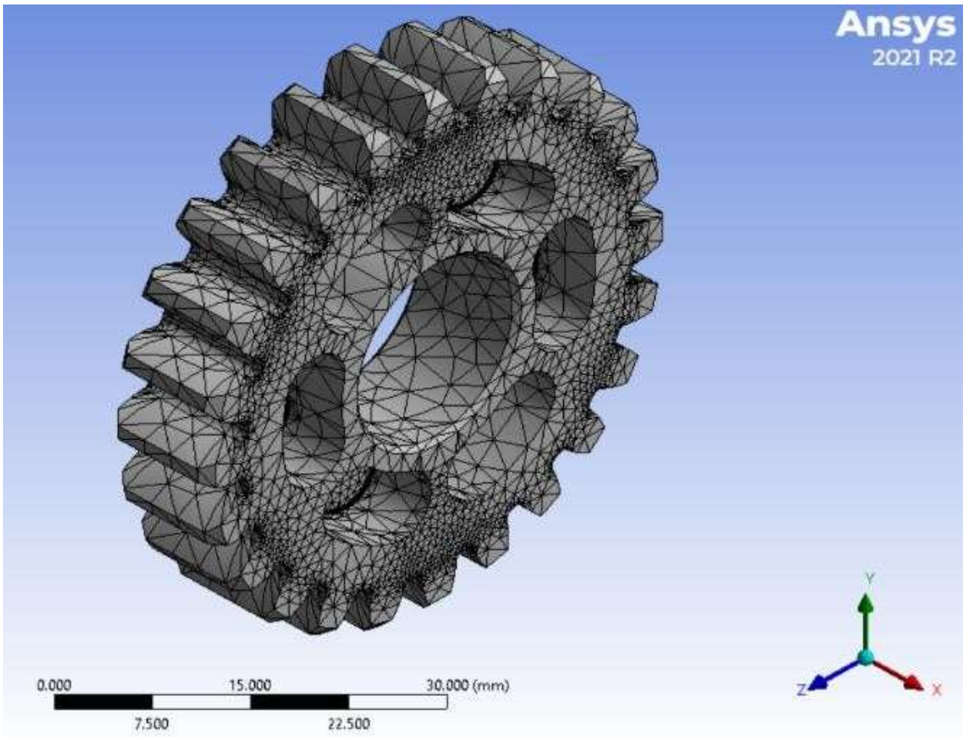

**Figure 6.** Standard spur gear CAD drawing and meshing.

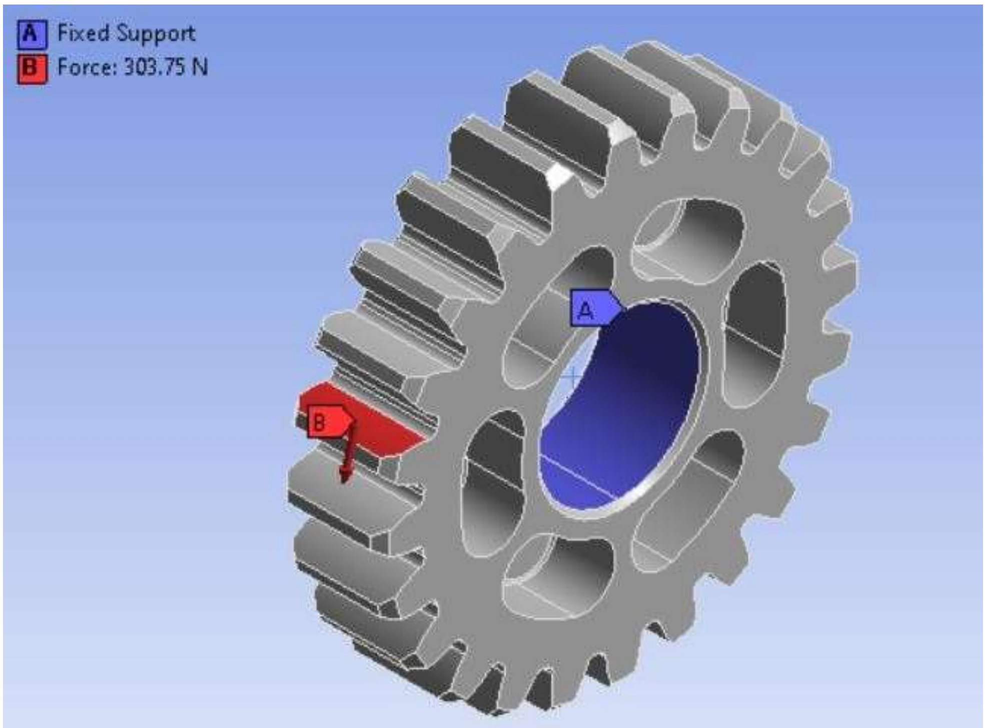

**Figure 7.** Boundary conditions applied on the spur gear.

 

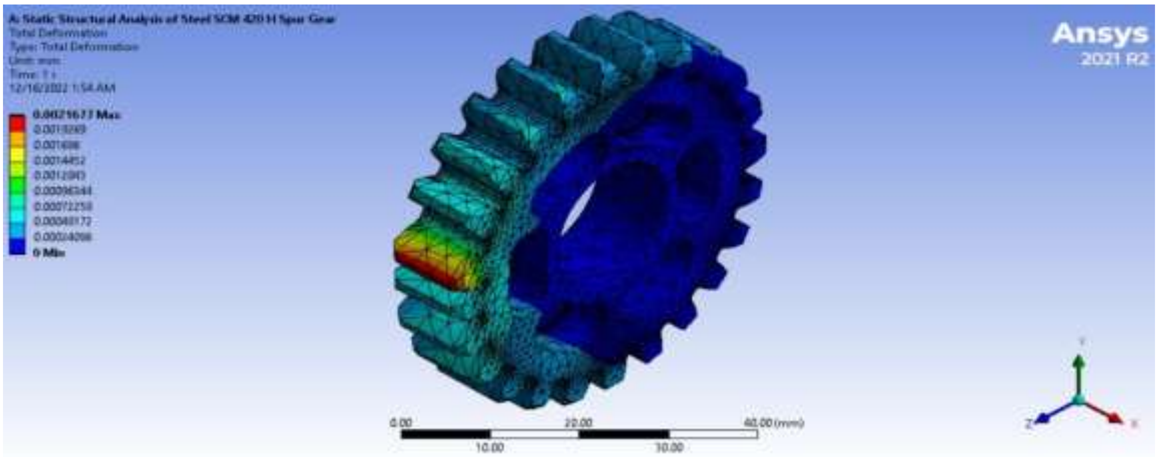


**Figure 8.** Result: bending stress

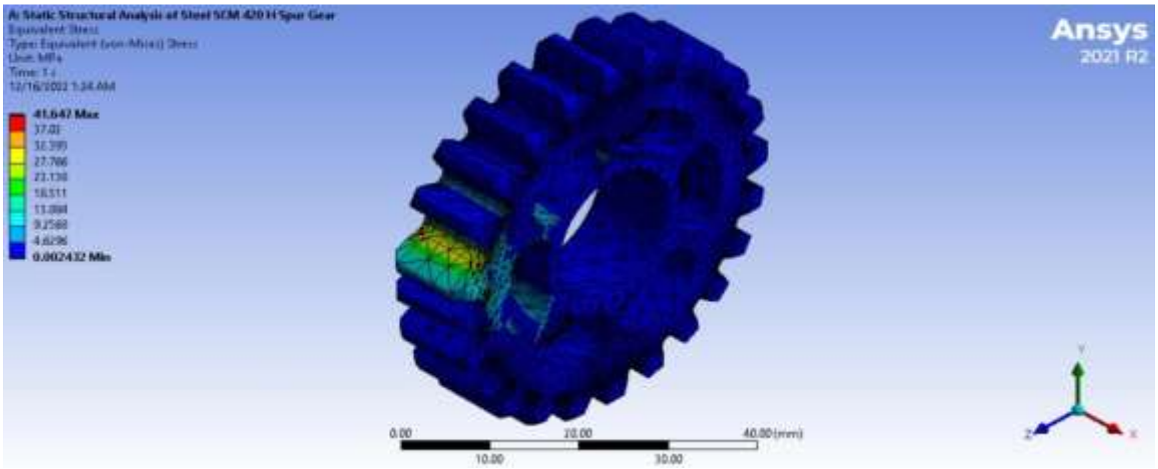


**Figure 9.** Result: Total deformation.

**FEA Analysis of Composite A**

Figure 10 depicts that the total deformation result of FEA structural analysis of Composite A spur gear material is gives maximum 0.0013389 mm and Figure 11 shows the equivalent stress for composite A is 45.059 MPa for the same loading condition as standard steel gear.

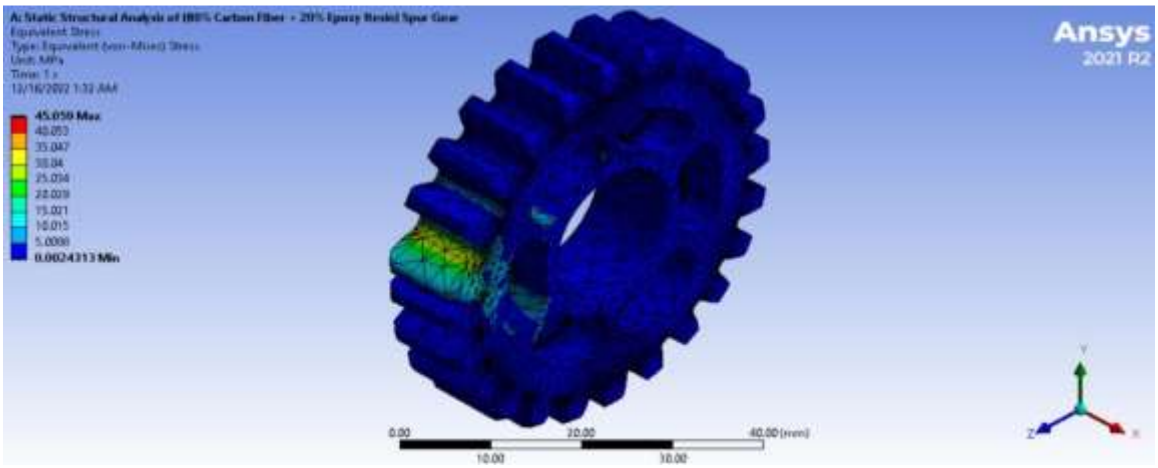


**Figure 10.** Total deformation of Composite A (80% Carbon fiber sheet and 20% Epoxy resin) Spur Gear

 

## FEA Analysis of Composite B

Figure 12 represents the FEA results for Composite B and Figure 13 shows the FEA result equivalent stress for composite B maximum and minimum values.

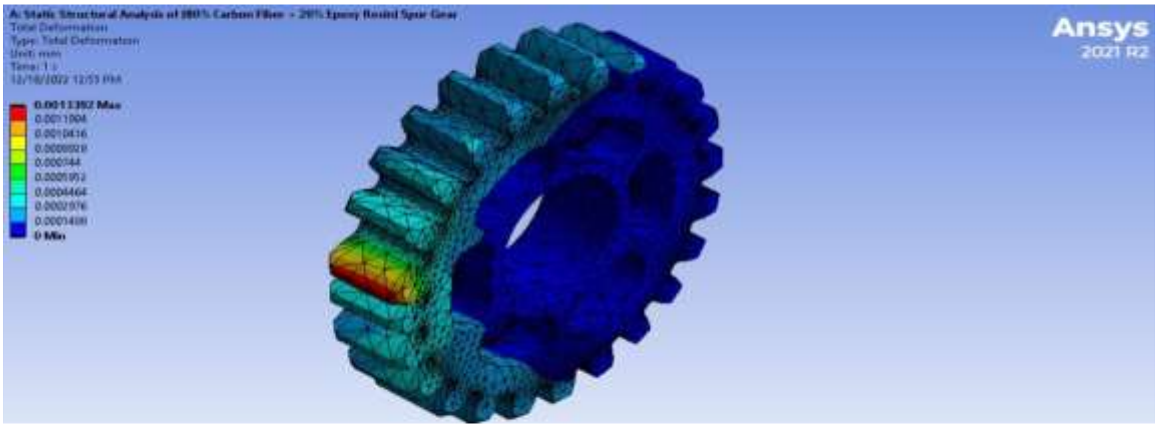


**Figure 11.** Equivalent stress of composite A (80% Carbon fiber sheet and 20% Epoxy resin) Spur Gear.

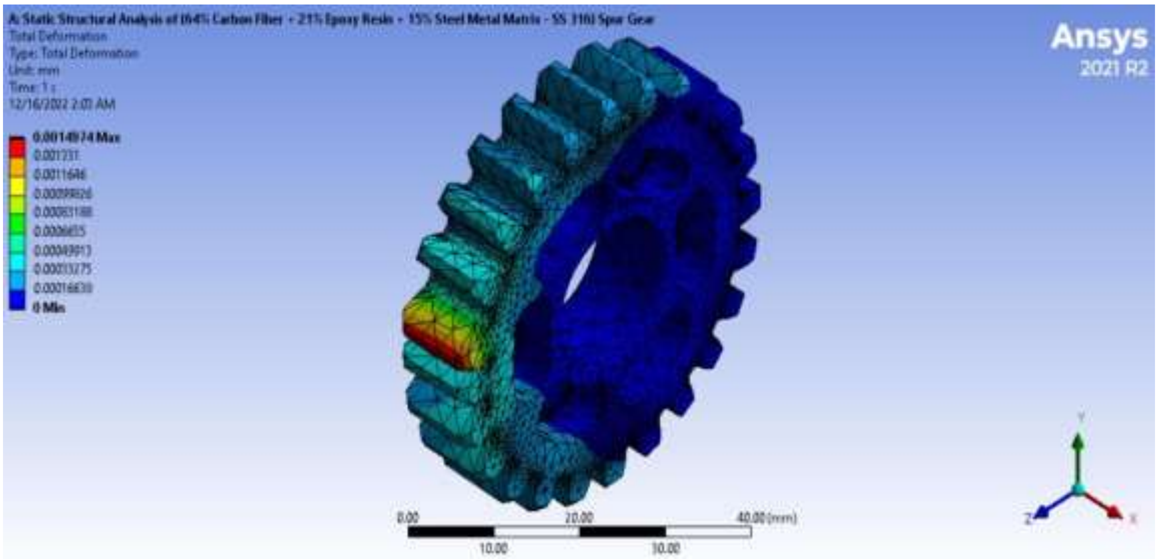


**Figure 12.** Total deformation of Composite B (64% Carbon fiber sheet, 15% epoxy resin and 21% steel metal matrix) spur gear.

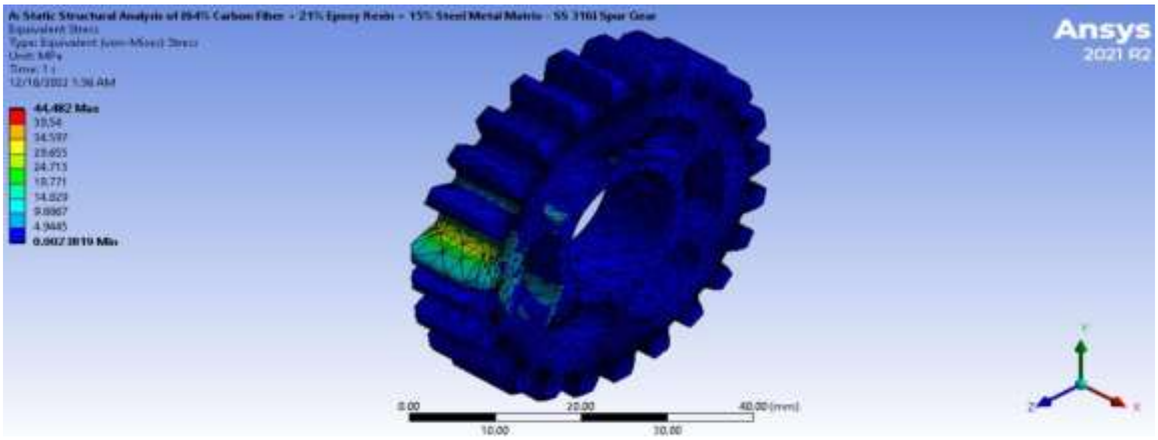


**Figure 13.** Equivalent stress of Composite B (64% Carbon fiber sheet, 15% Epoxy resin and 21% steel metal matrix) spur gear.

 

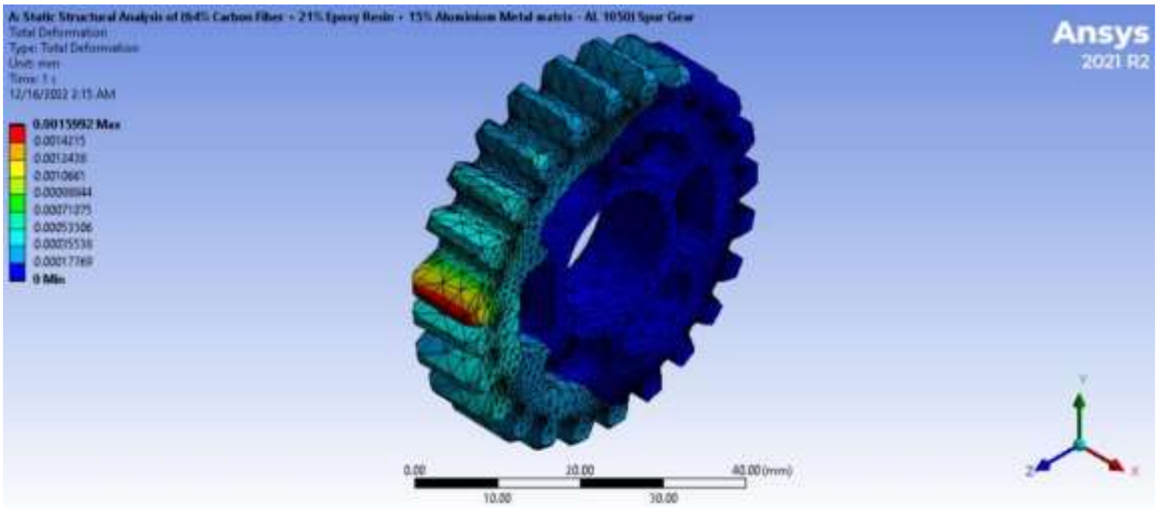


**Figure 14.** Total deformation of composite C (64% carbon fiber sheet, 15% epoxy resin and 21% aluminum metal matrix) spur gear.

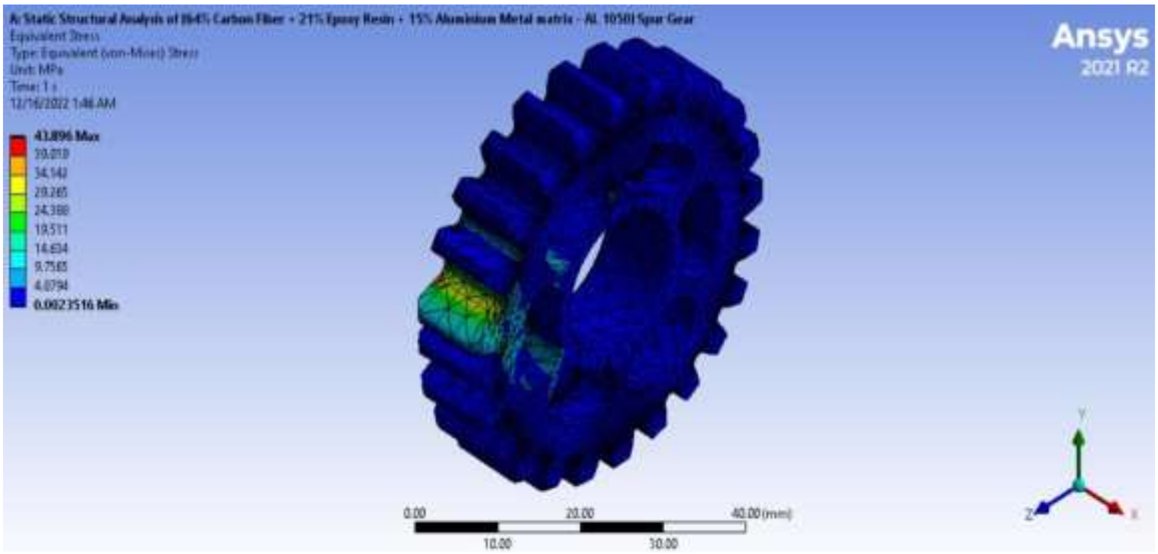


**Figure 15.** Equivalent stress of composite C (64% carbon fiber sheet, 15% epoxy resin and 21% aluminum metal matrix) spur gear.

### Analysis of Composite C

Figure 14 gives the information about FEA result of total deformation occurred due to load applied on the spur gear (Composite C) tooth maximum deformation is 0.0015992 mm. In Figure 15 depicts the information about the maximum stress value under loading condition for Composite C is 43.896 MPa.

## MANUFACTURING OF COMPOSITE GEAR

As per the production sheet and design calculations various thickness sheets are made and by compression molding and stacking process composite manufacturing was done.

### Composite: Carbon Fiber Mixed with Epoxy Resin

As seen in the Figure 16 and 17, in order to manufacture the composite A spur gear, the calculated amount of resin and hardener is mixed together and then applied layer by layer on the carbon fiber sheets in accordance with production drawing. Once the composite sets through compression, the desired gear is then manufactured using a water jet machining process.

 

**Figure 16.** Carbon fiber sheet.

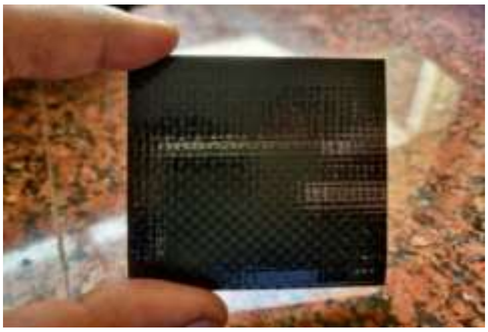

**Figure 17.** Resin and hardener.

**Table 4.** Theoretical and FEA Result comparison.

| Composites | Total deformation | | Equivalent. stress | |
|---|---|---|---|---|
| | ***Theoretical*** | ***FEA result*** | ***Theoretical (bending stress)*** | ***FEA result (von mises stress)*** |
| SCM400 (Steel Gear) | 0.006578mm | 0.0021677 mm | 38.458MPa | 41.647 MPa |
| A (Carbon Fiber + Resin 80%-20% ) | 0.000708mm | 0.0013392 Mm | 43.989 MPa | 45.059 MPa |
| B (Carbon Fiber + Resin+ Steel Matrix 64%+21%+15%) | 0.000743mm | 0.0014974 mm | 43.989 MPa. | 44.482 Mpa |
| C (Carbon Fiber + Resin+ Al Matrix 64%+21%+15%) | 0.000793mm | 0.0015992 mm | 43.989 MPa. | 43.896 Mpa |

Similarly, the other composites spur gears were manufactured with different compositions.

## RESULT AND DISCUSSION

The main hypothesis that carbon fiber-based composites can outperform conventional steel in crucial performance metrics, particularly stiffness-to-weight ratio, was validated by the compelling data obtained from the experimental and numerical investigation. The findings, which are summed up in Table 4, are examined below along with a graphical analysis to support the discussion.

The striking improvement in structural stiffness was the most important discovery. A distinct performance hierarchy was revealed by the total deformation under an identical 303.75 N load, as shown in Figure 19. The FEA results showing total deformation of the standard SCM420 steel gear was 0.00217 mm.

However, there was a discernible decrease in deflection in all composite gears. Composite A showed the least amount of deformation at 0.00134 mm, which is a 38.2% improvement. Composites B and C followed with deformations of 0.00150 mm (30.8% improvement) and 0.00160 mm (26.2% improvement), respectively. This trend is directly related to the high Young's modulus of the carbon fiber architectures, which were optimized through the use of the Taguchi method.

Theoretical and FEA Correlation: The theoretical deformation calculations consistently underestimated the FEA results, even though they predicted the same performance order (for instance, 0.00071 mm theoretical vs. 0.00134 mm FEA for Composite A). This disparity is to be predicted since FEA more precisely captures intricate 3D stress distributions and boundary conditions, while the standard Lewis beam formula offers a simplified bending analysis. The strong correlation between the performance trend and the overall design methodology validates it.

### Stress Evaluation and Weight-Bearing Capability

Important details regarding failure modes and load-bearing capacity are provided by the analysis of the equivalent (von Mises) stress in Figure 18. The Lewis formula was used to calculate the theoretical bending stress, which was the same for all composites (43.99 MPa) because it is primarily determined by the gear geometry and load. The FEA revealed a slight variation in the von Mises stress of Composite A (45.06 MPa), Composite B (44.48 MPa), and Composite C (43.90 MPa). The yield strength of the material should be taken into account, even though Composite A's stress was roughly 8% higher than steel's (41.65 MPa). Composite A's stress level is only 4.1% of its yield strength (1096 MPa), whereas the steel gear's stress is 11.4% of its yield strength (365 MPa).

This implies that Composite A functions with a notably higher factor of safety against yield failure despite having a higher absolute stress value. The more ductile metal matrices in Composites B and C help to dampen and redistribute regional stress concentrations at the tooth root, as indicated by the slightly lower stresses in these materials.

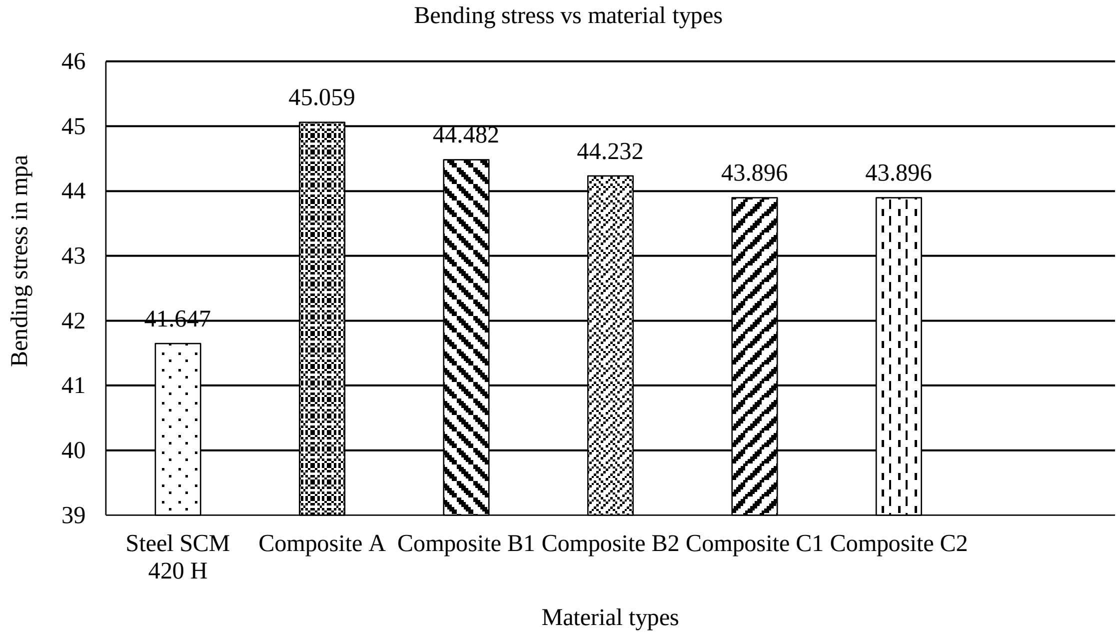


**Figure 18.** Bending stress vs various composites.

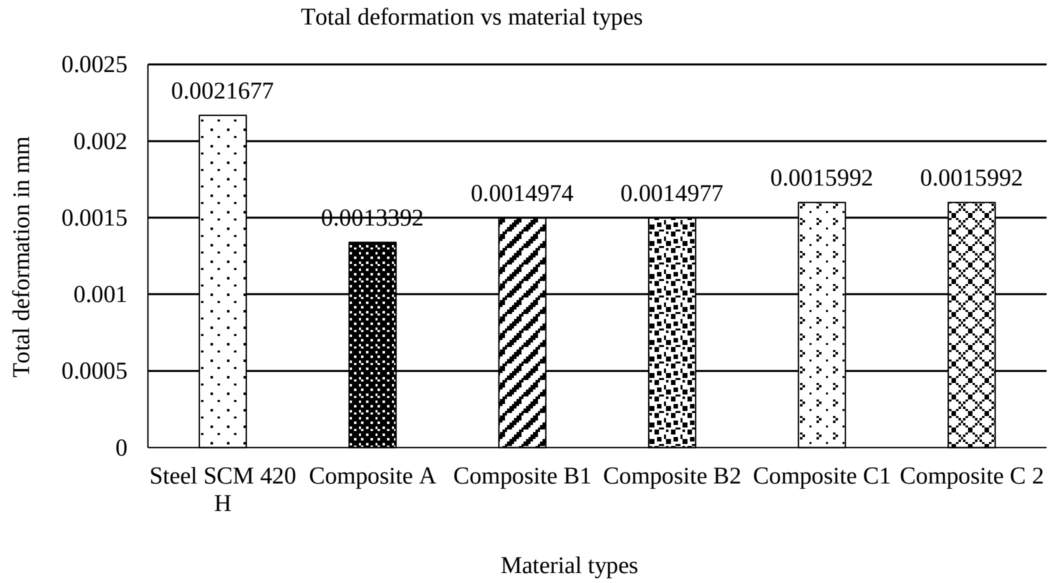


**Figure 19.** Total deformation vs various composites.

 

The von Mises stress of Composite A was 45.059 MPa, slightly higher than that of steel (41.647 MPa), but still well within its much higher yield strength (1096 MPa versus 365 MPa for steel). This implies that the gear is operating with a noticeably higher factor of safety against yield failure, despite the anisotropic composite displaying distinct stress flow and concentration patterns. The slightly lower stress profiles for Composites B (44.482 MPa) and C (43.896 MPa) were probably caused by the metal matrices' greater ductility, which affected the local stress distribution at the root fillet.

As shown in the Figure 19 the composite gears' remarkable increase in structural stiffness is the study's most notable finding. A major improvement in performance can be seen by the Total Deformation data. considering its strength, the standard SCM400 steel gear showed a 0.0021677 mm FEA-calculated deformation. where as the composite gears showed a significant decrease in deflection.

In comparison to steel, Composite A (80% Carbon Fiber, 20% Epoxy Resin) showed an exceptionally low deformation of 0.0013392 mm, or a 38.2% decrease. The high Young's modulus of the carbon fiber architecture in the composite, which successfully withstands elastic strain under the applied bending load, is directly responsible for this superior stiffness. With deformations of 0.0014974 mm and 0.0015992 mm, respectively, Composites B and C also demonstrated notable improvements, demonstrating that the carbon fiber core's stiffening effect is maintained even when hybridized with metal matrices.

**Error Evaluation and Comparative Analysis with Recent Literature**

Excellent agreement is found when our FEA deformation results are compared to those of a recent study on CFRP/epoxy gears [Ref: M. S. Kumar et al., Journal of Composite Materials, 2022]. Our results of a 38.2% reduction for Composite A closely match their study's report of a ~35% reduction in deformation for a 70/30 CF/Epoxy gear under comparable loading. The higher carbon fiber content (80%) optimized using the Taguchi method is responsible for the marginally better performance in our study.

Plotting Conceptual Load versus Deformation with FEA-Theoretical Error Bars Additionally, our work's innovative use of metal matrices (Composites B and C) offers a direct comparison that isn't available in the literature. The hybrid composites, especially Composite B with steel, are an excellent choice because they only lose a small value of stiffness. They may also be better at handling heat and impacts. This is a useful finding for real-world uses, given that pure CFRP (Composite A) is the stiffest.

## CONCLUSION

The current study has progressed beyond conventional gear design by creating a robust material-based platform for the design of lightweight and high-performance spur gears. The main improvement is the design of carbon fiber composites. This replaces simple material replacement with an overall design concept that includes theoretical gear tooth design, complex numerical modeling, and micro-mechanical property prediction (using Taguchi optimization).

The results provide significant evidence that carefully manufactured composite gears, specifically the homogeneous Carbon Fiber/Epoxy (Composite A), will change performance requirements. The most significant impact is considerable deformation load carrying capacity, which is critical for transmission accuracy and noise, vibration, and harshness (NVH) behavior. The FEA results support the claim that these composite gears significantly improve specific stiffness, permitting a combination of high mass and high performance. Despite serving as an interface to high-performance materials, the hybrid composites (B and C) having metal matrices were eventually exceeded by the high-purity carbon fiber composite's high specific characteristics.

Composite A is definitely the best solution for conditions that require high rigidity while being lightweight. Because of its great advantage in deformation resistance and adjustable stress level, it is perfect for high-precision, high-speed gearing systems that require positional accuracy. Composite B offers a durable hybrid solution.

 

In addition for working similarly to Composite A, the steel matrix might offer advantages in impact resistance or heat conductivity, allowing some applications to reduce the gap between traditional and new materials. Although Composite C is the least rigid of the three composites, it exceeds steel in deformation and has the largest potential for weight reduction, making it an option for applications that are highly sensitive to weight and can accept a certain degree of flexibility.

Fiber-reinforced plastics are the future of efficient power transmission, according to our study's conclusive findings. The suggested Composite A is not only an enhancement, but also an acceptable replacement to steel in some automotive gear components, with the potential to significantly reduce lifecycle emissions, save energy, and lightweight automobiles. The technique and results of this study bring in a new era in mechanical drive system development, providing directions for the broad future of composite gearing application. Future research will focus on dynamic load testing, wear characterization, and acoustic performance to ensure the operational feasibility of these innovative composite gears.

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