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EXPERIMENTAL AND NUMERICAL ANALYSIS OF MECHANICAL PROPERTIES OF CARBON FIBER-REINFORCED POLYMER GEARS

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Abstract: Composite materials emerge as better alternatives for replacing metallic gears in gear drive applications. Because composites have better mechanical properties, such as resistance to abrasion, don't require lubrication, produce less noise, and have high strength/weight ratios. It is considered that using composites in gears, which are an important machine element, will be extremely advantageous. This research aims to identify the mechanical properties of carbon fiber-reinforced polymer (CFRP) gears. To this end, a composite plate was created by vacuum infusion employing twill woven carbon fiber cloth as a reinforcing element and epoxy resin as a matrix element. This manufactured plate was used to cut the gear profile, which was then put through its paces. The tensile test was carried out to determine the strength of the samples cut from the plate. The modulus of elasticity and the tensile strength was found to be 62.85 GPa and 616.085 MPa, respectively, as a result of the test. After the strength tests, numerical analysis of the gear sample produced by the finite element method was performed. The results showed that composite gears would offer a good alternative to metal gears.

Keywords: CFRP gears; composite materials; vacuum infusion; finite element method; mechanical testing

INTRODUCTION

The increasing need for rigid and lightweight structures has led researchers and industry to composite materials. Composite materials have gained momentum in recent years as a viable alternative to traditional materials such as steel or aluminium alloys, in aerospace, automotive and other industrial applications. However, due to its advantages over metal gears, the use of polymer materials in gear transmissions is increasing. Polymer gears have been widely used in recent years, where the use of metal gears would not be very economical and typically with lower load requirements. Polymer gear transmissions are significantly less in weight than metal gears because the material properties of composites are very attractive for weight improvements. In addition, polymer materials have better noise, vibration, and stiffness (NVH) behaviour due to good damping effects. New environmental regulations have mandated different designs that focus on the global efficiency of the system to reduce greenhouse gas emissions and fuel consumption. One of the strategies developed due to such constraints is to reduce gear transmissions. High-speed fatigue behaviour of autoclave-cured carbon fiber reinforced polymer (CFRP) composite gears researched by "The mechanical properties of fiber-reinforced polymer composites are highly dependent on the strength of the fibers and the matrix and the adhesion between the two." It is important to investigate the performance of woven CFRP gears because of their potential to further increase load bearing capacity and wear resistance compared to short fiber reinforced polymer gears [1-2]. The thermal and mechanical properties of laminated CFRP composites are affected by the properties of their key components, such as the polymer matrix and reinforcing fibers, as well as the method of preparation of the laminate. Zhang et al (2016) performed quasi-static and dynamic tensile tests on unidirectional woven CFRP samples. While a characteristic effect of strain rate on tensile modulus and strength was observed in dynamic load tests, the significance of this correlation decreased in quasi-static tests [3]. Gear performance depends on the tribological behaviour of the gear pair at the contact interface. Bijwe and Sharma studied the effect of carbon fiber (CF) content ratio on the mechanical and tribological properties of CFRP with polyetherimide (PEI) thermoplastic matrix. With a fiber content of 65%, it has reached optimum results in mechanical and tribological properties [4]. As noted above, many possibilities exist to further improve the thermomechanical and tribological properties of composite gears. CFRPs can provide high mechanical strength, good thermal stability, high thermal conductivity and favourable tribological properties if a suitable manufacturing technique is used. This makes them ideal candidates for gears and other power transmission components. The purpose of this study is to make a comparison between metal and CFRP gears. It is aimed to fill the gap between the two gear types by using vacuum infusion cured, laminated CFRP gears. It is known that the use of polymer materials in gear transmissions is increasing due to their advantages over metal gears. Nevertheless, the subject contains gaps that are worth investigating and examining.

MATERIAL AND METHOD

In this section, design of spur gear is realized with programming mathematical equations. The parameters of rack cutter that generates spur gear are illustrated in Figure 1.

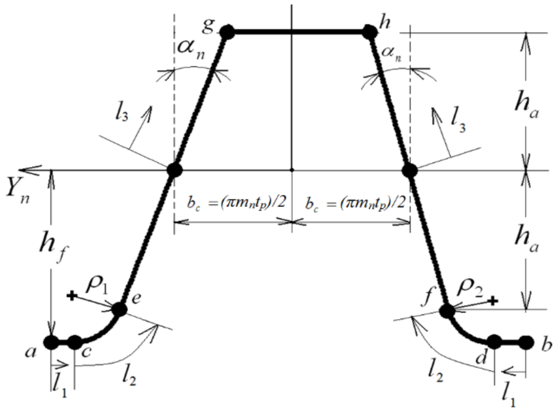


Figure 1. Parameters of rack

The equation of rack regions are given as matrix form in the following expressions;

ac-bd region

$$R_n^1=\begin{bmatrix}-h_f\\ \pm(\frac{\pi m}{2}-l_1)\\ 0\\ 1\end{bmatrix} \quad (1)$$

$$0<l_1<b_c-h_f\tan\alpha_n+\rho_{1,2}\tan\alpha_n-\rho_{1,2}\sec\alpha_n \quad (2)$$

ce-df region

$$R_n^2=\begin{bmatrix}-h_f+\rho_{1,2}-\rho_{1,2}\cos l_2\\ \pm(b_c+h_f\tan\alpha_n-\rho_{1,2}\tan\alpha_n+\rho_{1,2}\sec\alpha_n-\rho_{1,2}\sin(l_2))\\ 0\\ 1\end{bmatrix} \quad (3)$$

$$0<l_2<(\frac{\pi}{2}-\alpha_n) \quad (4)$$

eg-fh region

$$R_n^3=\begin{bmatrix}l_3\cos\alpha_n\\ \pm(b_c-l_3\sin\alpha_n)\\ 0\\ 1\end{bmatrix} \quad (5)$$

$$\frac{-h_a}{\cos\alpha_n}\leq l_3\leq\frac{h_a}{\cos\alpha_n} \quad (6)$$

Where, m is the module, z is the teeth number, $\alpha_{n1,2}$ is the pressure angle on sides, h_f is the dedendum, h_a is the addendum, $\rho_{1,2}$ are the tip radii, $l_{1,2,3}$ is the design parameter of cutter, b_c is half thickness of rack on pitch line.

$$n_n^i=\frac{\frac{\partial R_n^i}{\partial l_i}xk_n}{\left|\frac{\partial R_n^i}{\partial l_i}xk_n\right|} \qquad i=1\text{-}3 \quad (7)$$

where k_n unit normal vector of Z direction.

According the gearing theory, direction of sliding velocity vector between pinion and gear is parallel with tangent vector of common meshing point. Of course, it is always perpendicular to common normal vector. This expression is presented in Eq. (8).

$$n_n^i.v_{relative}=0 \qquad i=1\text{-}3 \quad (8)$$

During the generating process, the rack cutter makes a linear motion as $r_{p1}\times\phi_1$ whilst the gear as workpiece revolves as $\varnothing_1$. $S_1(X_1,Y_1)$ is the coordinate system of workpiece. Relationship between cutter and workpiece is shown in Figure 2.

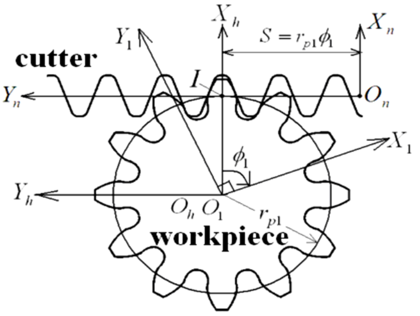


Figure 2. Relation between cutter and gear

Coordinate transformation matrix between rack cutter and workpiece is presented in the following equations.

$$M_{1n}=\begin{bmatrix}\cos(\varnothing_1) & -\sin(\varnothing_1) & 0 & r_{p1}\varnothing_1\sin(\varnothing_1)+r_{p1}\cos(\varnothing_1)\\ \sin(\varnothing_1) & \cos(\varnothing_1) & 0 & -r_{p1}\varnothing_1\cos(\varnothing_1)+r_{p1}\sin(\varnothing_1)\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (9)$$

$$R_1^i=M_{1n}{}^iR_n{}^i \qquad i=1\text{-}3 \quad (10)$$

Where M_{1n} is the coordinate transformation matrix and R_1 is matrix of involute spur gear, r_{p1} is pitch diameter.

With programming Eq.(1-10) in MATLAB program, the design points of involute spur gears are obtained. These points are exported to CAD to generate FE model. In Figure 3, design phases are given.

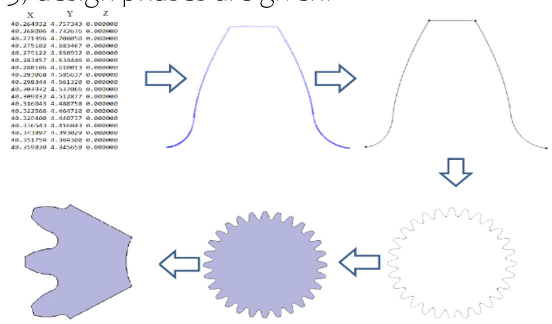


Figure 3. Design phases

First, sample plates were produced using epoxy resin with the fiber planned to be used. The carbon fiber fabric used in the study was 3K twill woven with a density of 245 gr/cm² and the epoxy used had the Duratek brand DTE 1200/DTS 2110 code. After determining the fabrics, resin, and vacuum values to be used, sample plates of 45*50 cm were produced by applying the steps of the vacuum infusion method. Glass plate was used as a mold during production. The composite sheet was removed from the mold after the infusion process and the necessary curing time, and the sample was cut in line with the TS EN ISO 527-4 tensile test standard. End-tab was adhered to the cut samples with epoxy adhesive and made ready for the tensile test (Figure 4).

Figure 4. CFRP samples prepared for tensile testing

After the above-mentioned processes, tensile tests were applied. These tests were carried out on the Besmak universal tensile/compression test device. According to the results obtained, the modulus of elasticity was 62.85 GPa and the tensile strength was 616,085 MPa for the CFRP sample.

FINITE ELEMENT ANALYSIS

In this section, finite element analyses were conducted for specific gear parameters. In Table 1, the parameter of case studies are illustrated.

Table 1. Gear parameters

Parameters	Case I	Case II	Case III
Module-m (mm)	2	2	2
Teeth number(z)	20	20	20
Pressure angle-α_n (°)	20	20	20
Addendum-h_a (×m)	1	1	1
Dedendum-h_f (×m)	1.25	1.25	1.25
Cutter tip radius- $\rho_{1,2}$ (×m)	0.38	0.38	0.38
Facewidth- b (mm)	1	1	1
Rim status	Solid	Thin	Solid
Material	Steel	Steel	CFRP

3 teeth model is prepared for finite element analyses. Meshing force (100 N) was applied at tip of tooth. Fixed support was given lateral sides and shaft hole. Boundary condition and mesh structure are presented in Figure 5.

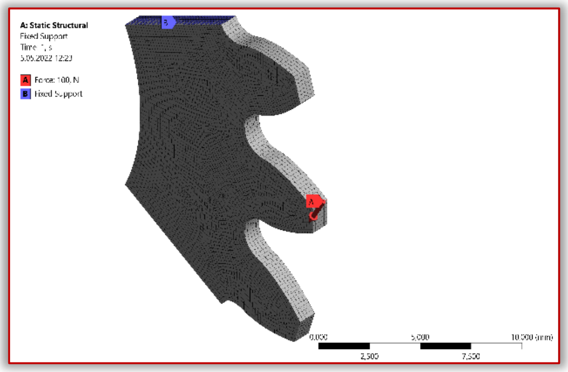
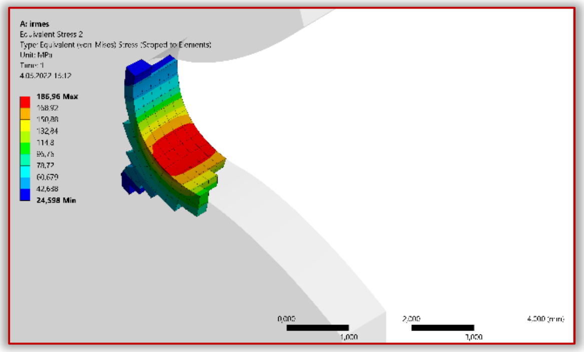


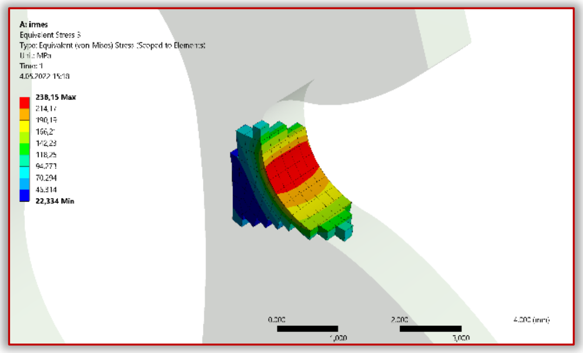
Figure 5. Mesh and boundary conditions

Hexahedral mesh type is used for discrete FE body with 0.2 mm edge length. For Case I and II, Young modulus and Poisson's ratio of material is taken as 210 GPa and 0.3, respectively. For Case III, CFRP material is modelled as isotropic material. Young modulus of CFRP is obtained as 62.85 GPa in the tensile test. For this reason, this value is taken as directly in numerical modelling.

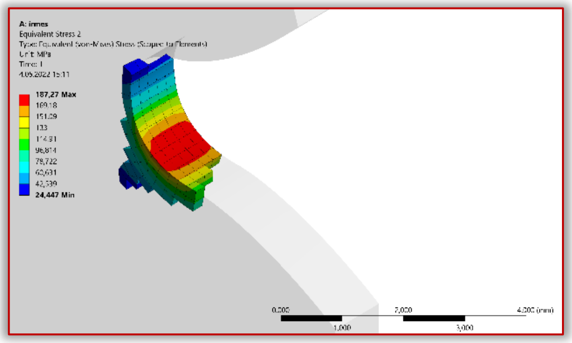
In Figure 6, the root stress results are given.



Case I



Case II

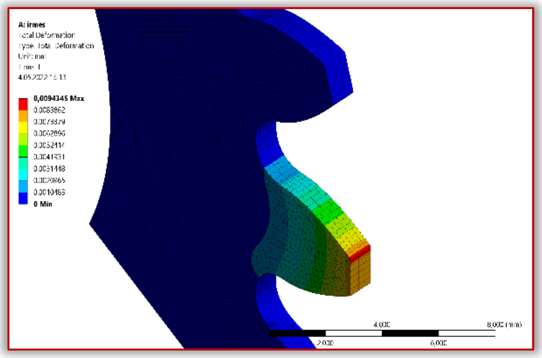


Case III

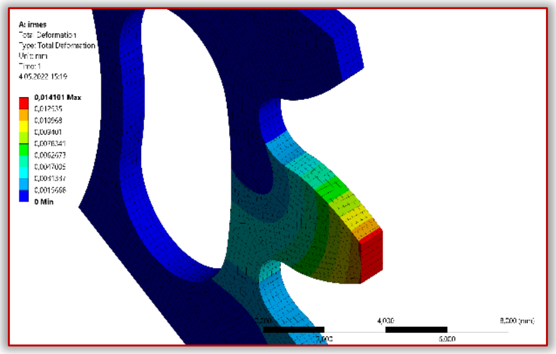
Figure 6. Root stress results

According to results, the material change slightly makes differences in root stress when the root stress results is examined for Case I and Case II (<1%). On the other side root stress of thin rimmed steel spur gear is approximately 30% higher than CFRP gear. Tooth deformation is another key parameter for spur gear performance. For this reason, tooth deformation values should be investigated. In Figure 7, deformation results are given for each cases.

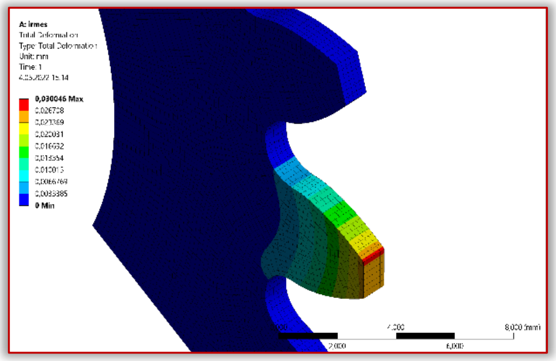
According to results, the Case I is found as the best option in terms of tooth deformation. CFRP gear deformation value is double of thin rimmed lightweight steel gear. Deformation is closely related with Young modulus. For this reason, these results are expected.



Case I



Case II



Case III

Figure 7. Tooth deformation results

CONCLUSIONS

In this study, the CFRP gear was compared with steel and light steel gear in terms of stress and deformation. For this aim, the 3D gear model was prepared for finite element analyses. To obtain the Young's modulus of composite material, tensile test was conducted. According to finite element analyses, the following points were obtained.

- CFRP gear is better than thin rimmed lightweight steel gear in terms of root stress. The root stress difference between solid rim steel gear and CFRP gear is found as rather low.
- CFRP gear is found as worst option in view of tooth deformation. Yet, when taken into consideration of the whole gear weight status, CFRP gear (1.40 gr) can be more advantageous than steel (6.6 gr) and lightweight steel gear (5 gr). Based on this fact, the tooth deformation of CFRP gear can be decreased with increase the face width.

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