Invited lecture/Research

Design Optimization and Fatigue Evaluation of Wood Composite Gears

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Abstract:
A great deal of research in polymer gears has gained importance in the last decade. It is necessary to highlight the different polymer materials and fibers used for gears to meet the requirements of a particular drivetrain application. With the increasing need to recycle already used materials, there are trends towards the use of BIO-based materials that would allow recycling and reuse in secondary, less demanding parts or assemblies. To integrate these materials into a real mechanical part such as a gearbox, their mechanical, thermal, and tribological operational performances must be evaluated. In this study, life tests of wood-polymer composite gears were performed using High-Density Polyethylene (HDPE) reinforced with 20% spruce fibers and the same polymer matrix reinforced with 20% beech fibers. The wood-polymer composite gear was tested with a mating steel pinion. The study aimed to determine the life cycles to failure of wood-polymer composite gears, the temperatures generated in the gear pair contact, and the flank wear characteristics of both types of wood composite gears. The results show that HDPE with beech fibers lasts on average 15% longer compared to HDPE with spruce wood fibers. When analyzing the flank wear, the beech fibers proved to be more wear-resistant than the spruce fibers in the same polymer matrix. The analysis of the failure mechanisms shows that the crack propagation at the tooth root is slower in HDPE reinforced with beech fibers compared to HDPE with spruce fibers due to the better mechanical properties.

Keywords: High-density polyethylene; Wood; Fibers; Gears; Fatigue; Wear.

1. Introduction

1.1. Background of using polymer-based gears

Gear wheels produced from polymer materials have been used for power transmission for a long time. Initially, polymer-based gears were used in less demanding power transmission systems where they were not subjected to high loads and consequently generated excessive mechanical stresses and heat in the contact zone. Nowadays, they play an important role in various mechanical drive systems as they offer advantages over metal gears, in particular wear resistance, dry running capability, low weight and inertia, self-lubrication, improved noise, vibration, and harshness (NVH) behavior, etc.

Polymeric materials comprise a large group of plastics. The most used polymers for gears are thermoplastics. Thermoplastics consist of two main groups, namely crystalline and amorphous plastics. The most typical crystalline polymers are the following: Polyacetal - POM, Nylons - PA, Polyethylene - PE, and High-Density Polyethylene – HDPE, (Ehrenstein, 2001). Given the current environmental concerns regarding the green future, engineers and researchers have started to perform various mechanical, thermal, and fatigue tests on different BIO-based polymer materials for potential gear applications to evaluate their durability and tribological performance. One of the polymers that can be easily recycled is the polymer HDPE, as it has no branching and its structure is more densely packed, making HDPE a linear polymer. By adding natural wood fibers to the polymer matrix, the mechanical properties of the resulting composite (Wood Composite Polymer – WPC) can be improved in terms of flexural strength, which has a favorable effect on the transfer of dynamic loads during the gearing process.

The intensive process of rolling and sliding speeds generates high temperatures in the contact between the meshing gear pairs, which causes the material properties to deteriorate with running. A fatigue process leads to an increase in the number of cycles when a gear pair meshes, resulting in a deterioration of the mechanical properties, which causes high elongation of the component due to the viscoelastic behavior of the polymers. Therefore, it is crucial to predict the wear-fatigue behavior for selected polymer gear pairs. To obtain these results, researchers need to optimize the material combinations of gear pairs through laboratory tests in the form of gear pair durability tests and measurements of tooth flank wear of selected polymer or polymer composite materials.

Ezzahrae et al. (2022) tested three HDPE composite mixtures with a WF content of 40%, 50 %, and 60 % and investigated the density, flexural properties, hardness test, and thermal analysis. The results show that increasing the wood content from 40 % to 60 % increases the density and hardness of the WPCs. In addition, increasing the proportion of wood flour to 60% reduces the flexural strength, while the flexural modulus increases.

Koffi et al. (2021a) evaluated the performance of extruded HDPE test pipes reinforced with 10-30 wt.% together with an adhesion promoter. They concluded that the newly produced composites can reduce the deformation of wood-containing material compared to pure HDPE. Young's Modulus can also be increased in proportion to the filler content compared to pure HDPE.

Afrifah et al. (2009) investigated nano clay-reinforced HDPE as a matrix for wood-plastic composites. The experimental results showed that the flexural properties of HDPE/wood flour composites could be significantly improved by a suitable combination of bonding agent content and nano clay type in the composites.

Koffi et al. (2021b) characterized the impact strength, Izod impact strength, hardness, tensile strength, and modulus of elasticity of birch fiber-reinforced HDPE obtained by injection molding of test specimens. They found that the improvement in tensile strength by 19.7% of the fibers was above average.

Černe and Petkovšek (2022) developed a thermomechanical model that provides results that are consistent with experimental measurements of polymer gears operated with high-speed infrared thermography.

Blais and Toubal (2020) evaluated the mechanical behavior of high-density polyethylene (HDPE) reinforced with short natural fibers using a test rig designed to monitor the flexural fatigue properties of gear teeth at high cycles. Fatigue as a function of the number of cycles was modeled using S-N curves, damage indices, and a linearised Weibull distribution.

2. Materials and Methods

2.1 Production of wood polymer composites

The selection of raw materials was based on the representation of various segments of the polymer and wood processing industry in Slovenia and throughout Europe. For the polymer matrix, High-Density Polyethylene (HDPE) was chosen as 3 mm pellets.
To improve the mechanical properties of the pure HDPE, spruce, and beech fibres were used. The argument for the choice of reinforcement was that these tree species are among the most widely cultivated in Slovenian forests and Europe. The average particle size of the spruce fibers was 0.2 mm and that of the beech fibers was 0.24 mm. The density of the pure spruce fibers was 140 kg/m^3 and that of the beech fibers was 155 kg/m^3. The moisture content of the wood fibers was 7% (Hriberšek & Kulovec, 2023). The following material mixtures were produced as part of the research: the first composite - High-Density Polyethylene (HDPE) reinforced with 20% by weight of spruce fibers (SF) and the second composite – High-Density polyethylene reinforced with 20% by weight of beech fibers (BF). To improve the adhesion between the HDPE matrix and the wood fibers, suitable promoters for polymers such as polyethylene PE-g-MA grafted with maleic anhydride were used. The composite material was extruded and chopped into small pellets of 3 mm size.

2.2 Gear production

The production process for the WPC gears consisted of drying the WPC pellets and injection molding the round semi-finished parts using the Krauss Maffei KM 50/100 CX machine. After injection molding, internal turning was performed to manufacture the gear hole. Dry machining was carried out using an involute hob cutter on a Koepfer 200 CNC machine. The steel gears were manufactured from round 42CrMo4 + QT steel, which was hardened (Q) and tempered (T). The bars were cut to a predetermined width to obtain circular half-parts. Facing was used to obtain an appropriate width for the circular semi-finished products. Internal turning was used to produce bores. The gear profile was produced using an involute hob cutter on a Koepfer 200 CNC machine. After machining, burrs were removed from the edges of the steel gears. To ensure the prescribed class of quality of the gear profile according to (ISO 1328-1, 2013) all test gears were checked with the 3D coordinate measuring machine (Wenzel LH 54, 2024). Figure 1 presents the produced gears. Table 1 presents basic gear geometry. Both, the driving steel gear, and driven wood polymer composite gear have the same geometry.

Table 1. Important gear parameters.

	Steel and WPCs gear
Teeth number, z [-]	20
Gear width, b [mm]	6
Gear module, m_n [mm]	1
Pressure angle at normal section, α_{wt} [°]	20
Tip diameter, d_a [mm]	22
Reference diameter, d [mm]	20
Root diameter, d_f [mm]	17.5

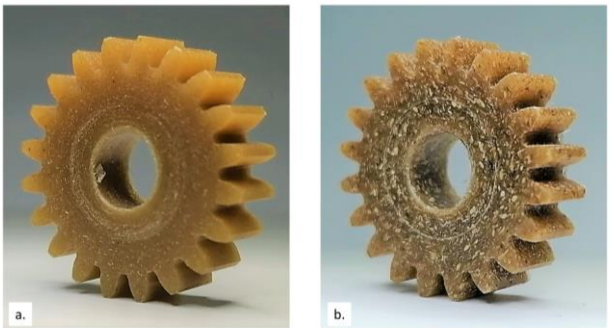

Figure 1. a. HDPE reinforced with 20% wt. spruce fibers and b. HDPE reinforced with 20% wt. beech fibers.

2.3 Testing procedures

The durability tests for polymer-based gears were conducted in a special test rig (see **Figure 1**). The test rig consisted of two 3-phase (4-pole) asynchronous squirrel cage electric motors with a frequency of 50 Hz and a power of 0.37 kW connected to two 1-phase frequency converters (power of 0.4 kW), the aim of which was to regulate the speed of gear 1 - driving and gear 2 – driven motors. The precision of setting the center distance of the gear pair was ensured by a linear rail with an accuracy of 0.001 mm. The required transmission of the rotary motion from the asynchronous motors was ensured by a belt with the appropriate transmission ratio on a pulley to the driving and driven shaft on which the gearboxes were mounted. The speeds of the individual motors were controlled by the corresponding frequency converter, with motor 1 acting as the drive source and motor 2 as the brakes source. The load acting on the shafts/gears was defined as the difference between the excitation frequency of motor 1 and the excitation frequency of motor 2. During the lifetime experiments of each gear pair, an average point temperature was measured and monitored in the meshing area. The thermal camera had a refresh rate of 50 Hz a display with a refresh rate of 20 Hz and a measurement area size of 2 x 2 mm. The device was connected to a PC on which the temperature distribution on the gears was visualized during a test. The gear pairs (steel/ HDPE 20% wt. spruce fibers and steel/ HDPE 20% wt. beech fibers) were tested under different torques (from 0.6 to 0.3 Nm), which were defined because the operation of a single gear pair had to reach from 100,000 cycles to several million cycles to characterize the fatigue life of each gear pair material. The speed of the gear pair was 1400 rpm and was tested at ambient temperature in the laboratory. **Figure 2a.** presents an experimental testing setup for durability testing of selected gear pairs and **Figure 2. b** presents an example of the tested gear pair.

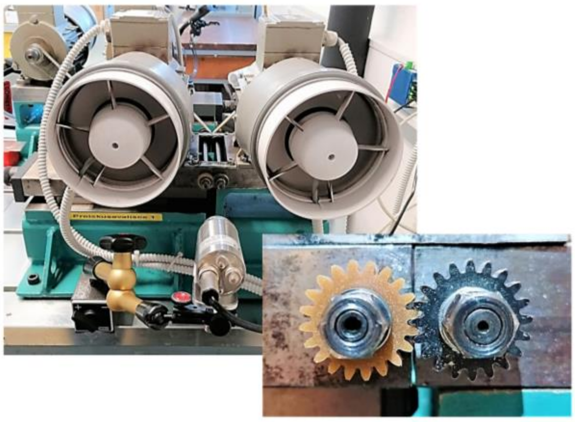

Figure 2. Experimental setup for durability gear pair testing.

During and after testing the durability of the gear pairs, wear measurements were carried out using an optical scanner. The measurement process was conducted at ten times magnification. The measuring range was 2 x 10 mm. The resolution of the measuring device was set to 100 nm in the vertical direction and 4 μm in the lateral direction. The contrast of the monitored image was 1 and the exposure time of the measurements was 1.4 ms. **Figure 3a**. presents the optical 3D scanning process and **3b.** the scanned 3D profile of gear tooth.

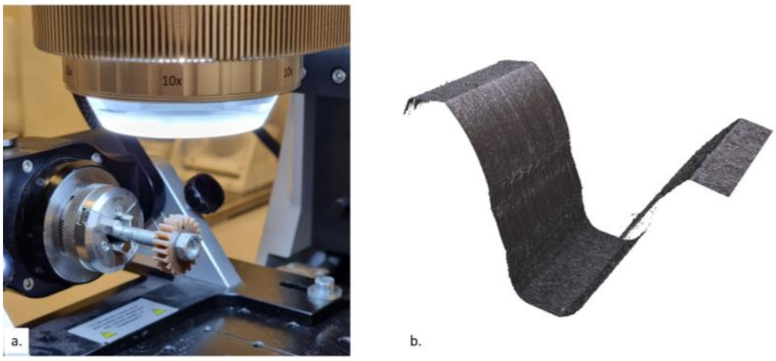

Figure 3. a. Optical scanning process of gear and b. 3D scanned profile of gear tooth.

The wear coefficients for each material were calculated using the calculation method cited in the VDI 2736 guideline. The VDI 2736 guideline defines a calculation method in which the abrasive wear of dry-running gears is evaluated. The wear coefficient k_w (10^{-6}/mm^3 Nm) can be calculated using the following equation (VDI 2736, 2016; Djebli et al., 2014),

$$k_w = \frac{W_m b_w z\, l_{Fl}}{2\pi\, T_d N_L H_V} \quad (1)$$

Where W_m is the average linear flank wear (in mm), l_{Fl} is the length of the contact line (in mm), T_d is torque (in Nm), N_L is the number of load cycles, and H_V is the degree of tooth loss.

3. Results

To accurately determine the lifespan of each WPC material in the infinite time range of fatigue strength (from 100,000 to 3 - 4 million load cycles), the following load levels were applied to each gear pairing (driving/driven) combination (steel/HDPE 20% spruce fibers - SF and steel/HDPE 20% beech fibers - BF): 0.3 Nm, 0.4 Nm, 0.5 Nm, and 0.6 Nm. Each experiment was repeated at least three times with the same load to obtain a satisfactory statistical validation of the process. The durability experiments were conducted at a room/laboratory temperature of approximately 24.0°C ± 0.5°C and an ambient pressure of 1013 hPa. During the tests, the average contact point temperature was measured for each experiment.

Figures 4, 5, 6, and **7** show the experimental results in the form of graphs of temperature (T) and load cycles (N) recorded during the tests with the infrared thermal camera. Each T (N) diagram consists of three characteristic parts. At the beginning of the test, a clear increase in the temperature gradient is observed. This is related to the deformation of the WPC tooth flanks and the increased wear rate caused by the harder steel driving wheel. This area is referred to as the running-in phase. In the next phase of gear running, the gear mesh temperature stabilizes with a constant temperature fluctuation, which defines a phase of linear wear that lasts a large part of the time of an experiment. In the last part of the running process, an increased temperature oscillation is observed, which is due to the deterioration of the cohesion between the bonds of the composite material, leading to a progression of cracks and increased flank wear, failing one or more teeth. In the tested gear pair made of steel/HDPE 20% BF, lower temperatures occurred in the meshing zone than in the HDPE 20% SF gears at the tested load levels of 0.6, 0.5, and 0.4 Nm. In addition, the HDPE 20% BF gears exhibited lower temperature fluctuations compared to the HDPE 20% SF gears. The reason for the lower temperatures and the associated temperature fluctuations may lie in the lower modulus of elasticity of the HDPE 20% SF material. This can be a reason for higher deformations of the teeth due to bending loads, which leads to a higher spontaneous heat release in the contact between the gear pairs. If the heat is high enough to increase the temperature transition zone, the modulus of elasticity of this zone decreases significantly and the strength of the WPC material is reduced.

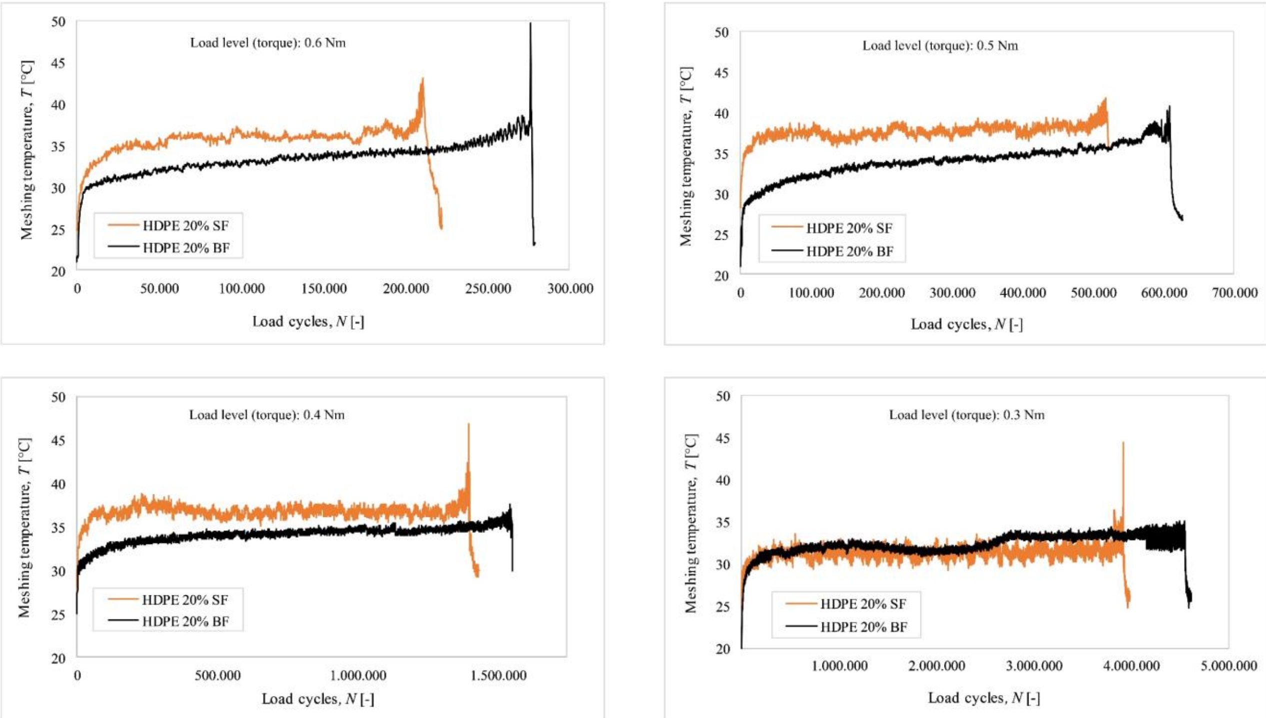

Figure 4. Comparison in durability testing results for observed gear pair combinations.

At the 0.6 Nm load level, the average difference in lifespan between the two WPC materials is 24%, while at the other three load levels, the difference is 10% in favor of the beech fibers. The results of the service life confirm that the composite material with beech fibers has a higher impact strength and consequently a better resistance to fatigue during the cross-linking process.

The conceptual procedure for the wear measurements was to perform each measurement just before the first tooth root fracture of each wood-polymer composite gear under the tested load levels. The wear of the flank profiles was analyzed in the 2D plane using a suitable calculation program at seven different gear diameters to obtain sufficient data to calculate the average linear wear of the flank profile. The wear coefficients of the materials were calculated based on the calculated average linear wear (**Figure 5**).

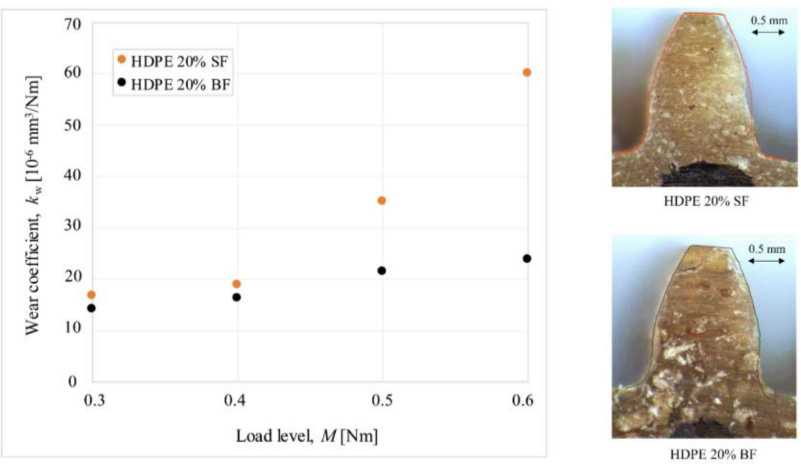

Figure 5. The dependence of wear coefficients on load level.

In **Figure 5**, At load levels of 0.3 and 0.4 Nm, the wear coefficients for both WPC materials are similar. At a load level of 0.5 Nm and even more clearly at 0.6 Nm, the wear coefficients for WPC with spruce fibers increase significantly compared to the wear coefficients for WPC with beech fibers. An important aspect when considering the wear properties of polymer-based materials is the mechanical properties of the polymer gear wheel when it is connected to a steel pinion. A higher modulus of elasticity can lead to better wear resistance of the flank profile, especially when considering materials with beech fibers compared to materials with spruce fibers. A lower modulus of elasticity could also have an indirect effect on the generation of higher temperatures in the meshing zone, which can also lead to higher wear of the gear, as can be seen in the case of gears with spruce fibers. The increased wear coefficient of the WPC with spruce fibers at 0.6 Nm can lead to a shorter lifespan of the test specimen.

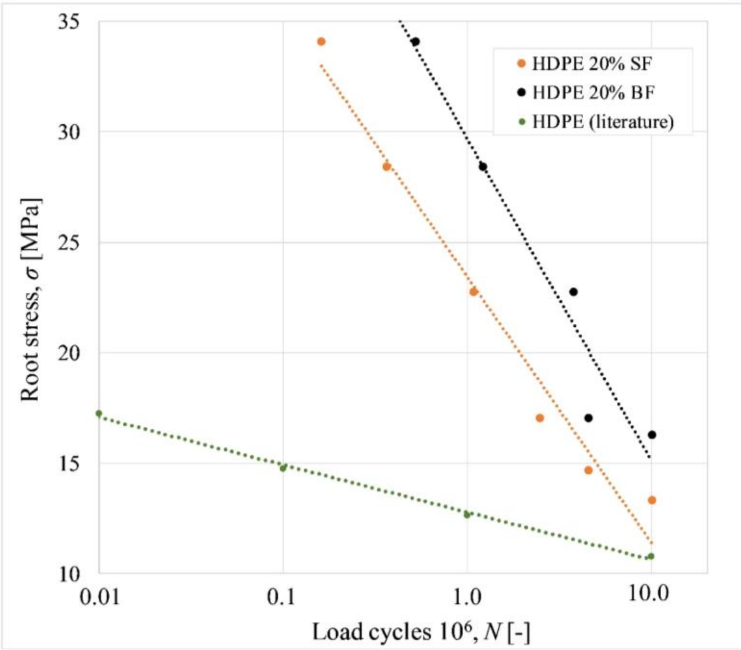

Figure 6. Stress-cycle (*S-N*) curves.

Based on the durability experiments and measured wear characteristics for both types of materials, fatigue life curves were modelled for both gear pair combinations. **Figure 6** presents the stress-cycle curve (*S-N* curve). To have a reference for the fatigue life of generic HDPE material, the S-N curve is added to the figure taken from the obtained literature. From the figure, it can be concluded a slighter better fatigue performance of HDPE reinforced with beech fibers due to better already described mechanical properties of the material and more resistant wear characteristics which prevent loss of material in the root and consequently shorter duration.

Figure 7 presents the failure mode of the observed wood composite gears. The failure mode is called tooth root fracture due to fatigue which is a consequence of the cyclic bending loads produced from steel driving gear synchronizing with meshing frequency. **Figure 7** presents the mentioned type of failure mode for each observed gear.

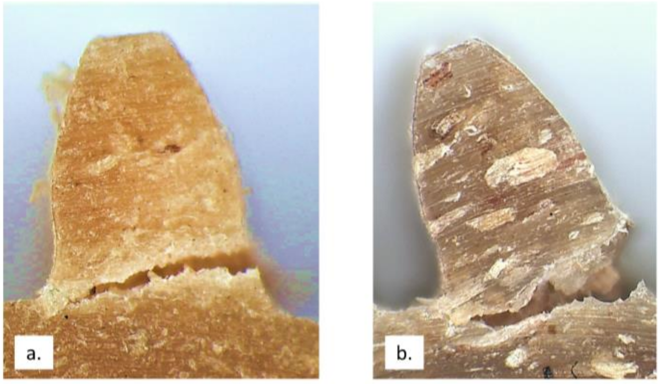

Figure 7. Failure mode: a. HDPE reinforced with 20% wt. spruce fibers and b. HDPE reinforced with 20% wt. beech fibers.

4. Discussion

When designing polymer-based gears, the main disadvantage is the lack of data on the fatigue strength of the various materials required for an accurate calculation for the selected gear application. This information cannot be found in the technical data sheets. Based on tests, it is possible to obtain data on the durability of gears, based on which the fatigue strength of the material can be calculated in the form of *S-N* lines.

This paper demonstrates the use of high-density polyethylene (HDPE) reinforced with equal weight percentages of natural spruce and beech wood fibers to produce gear components suitable for load-level power transmission applications, such as domestic drive mechanisms. As part of the research, blends of HDPE reinforced with 20% spruce fibers (SF) and HDPE reinforced with 20% beech fibers (BF) were produced to characterize and evaluate the performance of wood polymer composites (WPC). This could lead to the formation of a new material database in the field of material conversion data and the possibility of introducing materials into specific applications shortly, with the prospect of promoting sustainable green engineering in terms of reuse after the recycling process.

From the results of the experimental research and analysis, it can be concluded that the experiments show overall better operational properties of the gear pair with beech fibers compared to spruce fibers in the HDPE matrix. The composite material reinforced with beech fibers withstands the cyclic fatigue loads that occur during meshing better than the composite material reinforced with spruce fibers. The fatigue life achieved and wear rates for the two composites tested are comparable to the results found in the literature by Bravo et al. (2018) and Ghazali et al. (2017) in the field of testing BIO-based polyethylene. The calculated wear coefficients for the tested composites show satisfactory wear resistance depending on the applied loading conditions. The typical failure mode is tooth root fracture.

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Conflicts of Interest: The authors declare no conflict of interest.

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