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Material Characterisation

Gear fatigue life and thermomechanical behavior of novel green and bio-composite materials VS high-performance thermoplastics

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ABSTRACT

In many applications, metal gears have been replaced by plastic gears because of their functionality and cost advantages. Despite their many benefits, the intensive use of plastics and composites raises sustainability issues because of the depletion of non-renewable petroleum resources and the pollution that is generated. Thus, alternative ecological solutions for plastic gears are necessary; however, little is known regarding ecologically designed gears. In this study, we propose two types of innovative gear materials. The first is a semi-ecological polyethylene bio-composite gear reinforced with birch fibers, and the second is a fully bio-sourced natural polyethylene gear with birch fibers. This study is the first time such fully ecological composite-plastic gears have been tested. The tests record the evolution of the fatigue and temperature over time under various operating conditions. Furthermore, acoustic emission is used to assess the evolution of fatigue cracks. The results indicate that the fully ecological gears are feasible and offer an alternative to traditional materials, such as engineering plastics, likely at a lower cost.

1. Introduction

The use of plastic gears for the transmission of motion is growing [1,2]. The evolution in the understanding of plastic gears has led to their widespread utilization in most appliances of daily life. According to an analysis by the Freedonia Group, applications of plastic gears increased by 83% between 2003 and 2013. This increase represented $ 1300 million in 2013 against $ 710 million in 2003 [3,4]. Currently, plastic gears are often immediately chosen for many low-torque applications. However, despite their many advantages, the intensive use of plastics and composite materials with a polymeric base raises sustainability issues because of oil depletion and the pollution they cause. Pollution that is associated with plastics leads us to consider applications where plastics could be replaced by other materials, at least partially [3].

Plastic gears have been replacing metal gears because of their financial advantages in mass production [5]. The market values the cost-effectiveness and specialized features of plastic gears (e.g., reduced density, inexpensive production, capacity to function without oil or grease); therefore, plastic-type gears have been increasingly used [6,7]. Examples of the range of applications for plastic gears include food and textile machinery, office machines, household utensils, and the automotive industry [6–8].

The main dissimilarities between the behaviors of metallic and plastic gears are related to the elastic moduli of plastics, which are approximately one hundred times lower than the elastic moduli of steels. Plastic gear meshing includes an enlargement within the contact between the teeth outside the line of action before the beginning and after the end of the theoretical engagement [9]. The massive deformation of a tooth in the meshing minimizes the stress of every pair of teeth in contact [10]. In addition, this low modulus lowers the stress limit that is supportable by the gear, thus limiting its utilization to low torques.

Several constraints are observed when comparing plastic gears and metal gears, including the operating temperature, thermal expansion, capacity, dimensional stability (low because of shrinkage), and moisture absorption [2,11,12]. The temperature dependence of certain properties is problematic. For example, thermal breakage joins metal gears. These characteristics are limiting factors in plastic gear design. Thus, only plastic with high

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mechanical properties, such as nylon and acetal, are used for heavy duty plastic gears in practice [2,13]. These high-performance plastics are commonly called engineering plastics and are expensive compared to other plastic solutions, in addition to having a very limited ecological contribution to the gear's life cycle (See Fig. 1).

Intensive use of these materials obviously causes additional problems for human health and the environment. Nevertheless, the overall use of plastics is constantly increasing, as shown in Fig. 2. The only exception of this trend was approximately 2008, when the world suffered from an international financial crisis. Considering this exception and its context, the trend is that the use of plastics in the world is likely to constantly grow in the future.

This trend is an important concern. Despite these materials' many benefits, the intensive use of plastics and composites raises sustainability issues because of the depletion of non-renewable petroleum resources and the pollution that is generated.

However, the past decade has seen increasing use of ecological materials, specifically in the form of natural fibers, which are used as reinforcements in composite materials, because of increased environmental awareness. In addition to being recyclable, composite wood fiber (bio-composites) has appealing mechanical qualities and thus rivals non-degradable materials in several application fields [15,16].

Amid various other environmentally friendly options, a remarkable form of composites with structurally reliable attributes has been created: (PE) with birch fiber. PE is regarded as an economical thermoplastic and has the largest production share of any polymer type, which represents 29.1% of the world's plastic generation [17,18]. PE is achieved via the polymerization of ethylene (C_2H_4), which yields macromolecules with a repeating monomer unit ($CH_2 - CH_2$) [19,20]. In addition, one of the most accessible natural fillers in the province of Québec is birch fiber. Because this hardwood tree grows in cool areas with abundant precipitation, this area comprises approximately 50% of the growing stock volume of yellow birch in North America [21]. The mixture of both of these materials creates an eco-solution via a bio-composite that is straightforward to produce and thus could be extremely economical.

The development of such an environmentally friendly composite with a natural fiber content below 50 wt% (i.e., with thermoplastics as the principal element of the matrix) is possible by employing a bio-sourced matrix and natural fibers. In the event that the entire composite is bio-sourced, the term “green composite” is used. Among the green matrix materials that exist, polyhydroxyalkanoates (PHAs), polylactides (PLAs), and bio polyvinyl chlorides (PVCs) tend to be of particular interest [22–27]. All these

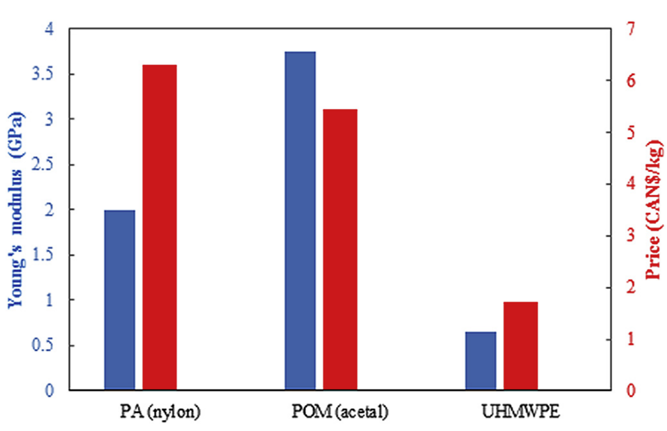

Fig. 1. Relationship between the price and mechanical properties of the typical materials that are used in plastic gears. Adapted from [3].

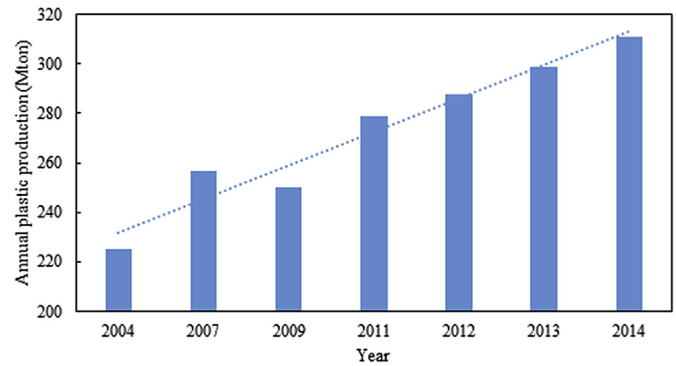

Fig. 2. Increase in global plastic production in recent years. Adapted from [14].

materials display no resemblance to PE; however, a 100% environmentally friendly PE-based composite became feasible when Braskem, a Brazilian petrochemical company (and America's top producer of thermoplastics) [28], created a “natural (green) polyethylene” (NPE) that was fully procured from sugarcane. This composite was an engineering breakthrough because the two materials possessed the same mechanical attributes yet were sourced in different ways. As reported by Braskem, green PE presents ecological benefits within life cycle assessment (LCA) compared to conventional PE: this polymer captures 2.5 tons of CO_2 per ton of product [29]. Currently, several end users are using NPE (e.g., Johnson & Johnson, Nestle, Toyota, Danone, P&G) [29].

Green and bio versions of these PE-birch composites have been studied in the past. These materials were developed and their mechanical characteristics were characterized [16]; the differences between their damage behaviors were elucidated [30]; and their specimen fatigue behaviors were studied [31]. Nonetheless, a knowledge gap exists in the understanding of the gear damage behaviors of the green and bio versions of composites when used in a demanding real-life task, such as gears, and how these materials perform compared to traditionally used materials. To our knowledge, a green is bio-composite that is based on PE has never been produced for use in spur gears.

For example, Kržan and Vižintin [32] investigated universal tractor transmission oil in a series of tests to evaluate vegetable-based oils. Ester-based oils exhibit lower friction coefficients than higher-additive mineral-based oils but increase wear. Michalczewski, Piekoszewski [33] manufactured heavy-loaded machine components of steel that were covered with low-friction coatings to allow for the use of environmentally friendly oils to reduce environmental pollution. Medvecka-Benova and Bigos [34] approached ecological gears from the perspective of sound. Noise is an alarming ecological aspect of machines and machinery because of regulations.

The literature fails to address the ecological issues of ecological gears while focusing on the construction materials, mainly because of the technological limits that have been imposed until very recently. In this sense, the most notable work toward an ecological gear was performed very recently by Itagaki, Takahashi [35], in which rice hull-silica-carbon (RHSC) was used as a reinforcing material in a plastic gear. Rice is eaten all over the world; in particular, the consumption of rice is the highest in Asia. Rice hulls are a residual product of rice and contain natural silica, i.e., approximately 20 wt%. The effects improved the fatigue strength of the injection-molded plastic gear.

The alternative that is proposed in this paper is the use of new ecological composites for utilization in gears. Experimental studies are conducted to characterize the mechanical behavior (heating and fatigue) of materials, including a comparison with commonly used technical thermoplastics such as nylon and polyamide. The goal of this study is to understand the composites' thermo-mechanical damage to verify their feasibility as real mechanical parts, such as gears.

The remainder of this work is organized as follows. First, the materials and methods are presented. Second, the thermal results are presented. Third, the fatigue results are presented. Finally, conclusions are drawn.

2. Materials and methods

2.1. Gear fabrication and materials

Industrial short fibers (thermomechanical pulping, #35 mesh size) of yellow birch (Betula alleghaniensis) were used in this experiment. The fibers were produced by the Lignocellulosic Materials Research Center (Trois-Rivières, Canada) and dried at 60 °C in an air-circulating oven for 24 h before use.

The two thermoplastic matrices that were used were HDPE (Sclair® 2909), which was donated by NOVA Chemicals, and NHDPE (SHA7260), which was donated by Braskem. MAPE (G2010), which was supplied by the Eastman Chemical Company (Kingsport, TN, USA), was used as the coupling agent (CA). The maleic acid graft content was 1.5%, with a molecular weight of 15,000. The CA's chemical composition facilitates the formation of chemical bridges between the natural fibers and PE matrix. The use of CA in quantities beyond 4 wt% can lead to self-entanglement among CA chains rather than entanglement in the polymer matrix [36]. For this reason, 3 wt% CA was used.

All the specimens were prepared using a two-roll mill (Thermon, C.W., Brabender, Model T-303) with a gear ratio of 0.6. The grains of the matrix were melted on rollers at 170 °C, and the fiber was subsequently added at a weight ratio of 40 wt%. Specimens were produced using a molding process at a temperature of 205 °C and using a hydraulic press for 20 min at a pressure of 10 MPa. One example gear that was produced by this methodology is shown in Fig. 3. The external visual aspect of the gears is the same, independent of the type of matrix.

Fig. 3. Example of a composite gear that was used in the tests.

2.2. Gear fatigue testing

The gears that used these new materials were simulated as in real operations. Because gear teeth experience cycling loads, their stress state varies cyclically, which explains the occurrence of fatigue failure when the load does not exceed the yield strength of the material. The testing machine for the plastic gears was a jailed pair machine, as shown in Fig. 4. The machine was initiated without load, and then torque was applied gradually without affecting the gear's rotation. This torque depended on the air pressure that was supplied to the actuator and was measured by a torque meter that was installed on the drive shaft. The air pressure in the cylinder was then controlled during operation via a control board to control the resistant torque that was applied to the gears.

The couple was controlled using closed loop software in a National Instruments LabView interface. A proportional-integrative (PI) controller was used in this study. The test rig's operational principle involved two gear sets: one slave gear and one test gear set. The slave gears were actioned by an electrical motor (Louis Allis®, Type PJMX, 575 V, 3 H P) that was coupled with a Cleveland® speed variator (Series 66A, size 6K42M). The motor was connected to a worm gear that drove the slave gear shaft. When the slave and test gears were directly connected, the system became a torque-regenerative system. Thus, the required input drive power only needed to overcome the frictional losses in the system. The restrictive load of the testing gear system was applied via a rotary pneumatic actuator. This device was located at one of the two shafts that linked both sets of gears. The other shaft contained a torque meter that converted the restrictive load into an electric signal. This information was acquired and controlled via an analog channel on a National Instruments® card (USB NI myDAQ). The slave gears were lubricated using a single oil jet at the in-to-mesh location. The tested gears were run dry.

2.3. Non-destructive testing

2.3.1. Thermal measurements

The temperature was measured using a FLIR A35 thermal imaging camera. This camera can read temperatures from −25 °C to 136 °C for a zone of 320 to 256 pixels at a refresh rate of 60 Hz. The tested gears were mounted to read their lateral faces (Fig. 5). The faces of the gears in the test were painted with high-temperature black paint. The supports and mechanisms of the test rig behind the gears in the test were hidden using black sheet of paper that was inserted prior to testing. The goal of this procedure was to guarantee uniform emissivity and no reflection for a complete camera field of view. The temperature of any given moment of the gear meshing can vary depending on the point of measurement, so the temperature that was used in this study was the maximum temperature for the entire thermal-image of the area near the contact between the gears.

2.3.2. Acoustic emission

AE measurements were conducted using devices that were provided by the Physical Acoustics Corporation (PAC) and equipped with two PCI cards. Two sensors (type Micro-80 PAC, wideband 100–1000 kHz) were mounted onto the supports for the tested gears (Fig. 6). The positions of the acoustic sensors were kept the same during all the tests. An acoustic threshold level was set at 50 dB to filter the background noise. A silicone adhesive gel was used as a coupling agent between the sensors and specimens. Before each test, the quality of the coupling was verified using a Nielsen-Hsu pencil lead break.

The quality of the measured AE data mainly depends on the choice of the waveform system timing parameters, namely, the

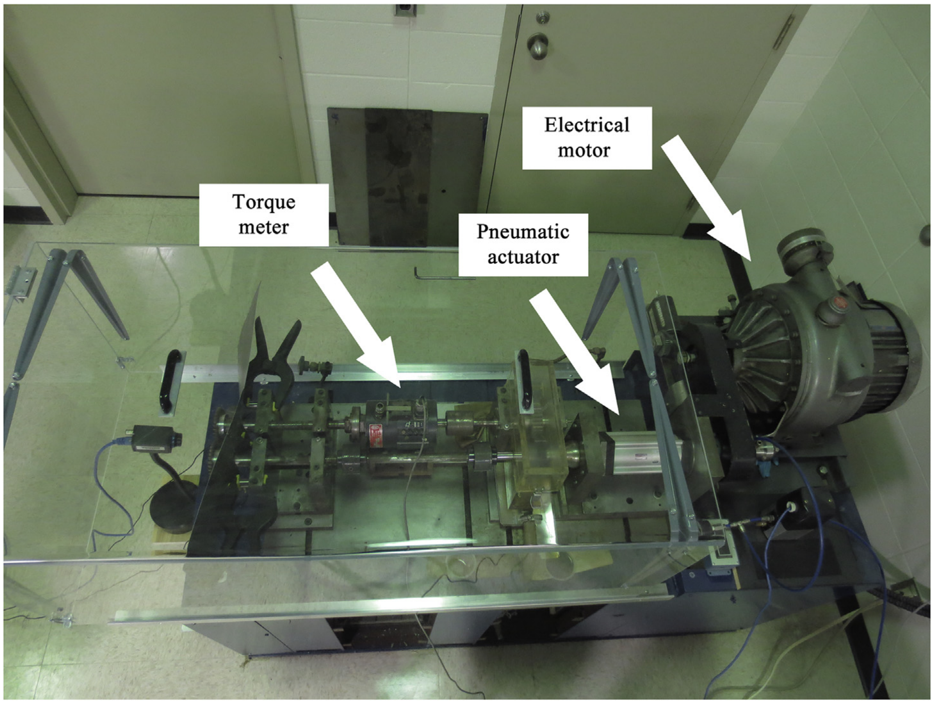

Fig. 4. Equipment that was used for the experimental testing of the gears.

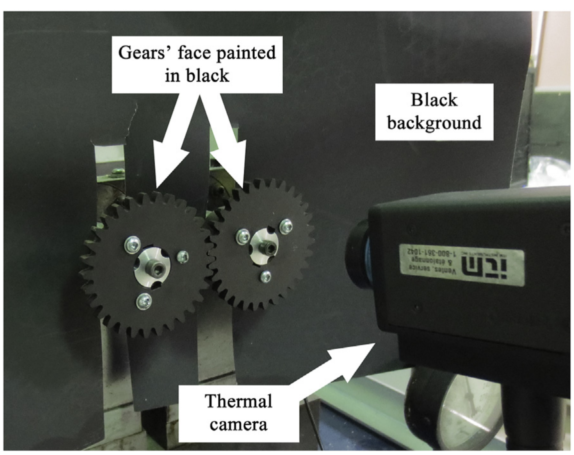

Fig. 5. Thermal camera that was used in the tests, with the gears painted in black.

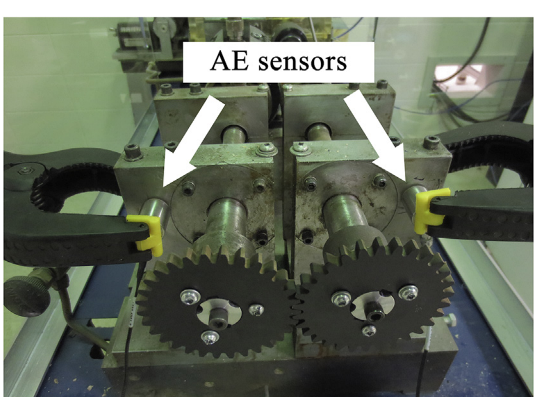

Fig. 6. AE sensors that were mounted on the supports of the gear test rig.

peak definition time (PDT), hit definition time (HDT) and hit lockout time (HLT). The employed values of these timing parameters were PDT = 40 μs, HDT = 80 μs and HLT = 200 μs [37].

3. Results and discussion

3.1. Temperature increase results

The general results of the stabilized temperature working conditions for all gears are summarized in Tables 1 and 2. The temperature increase in these tables indicates an increase in temperature up to a point of stabilization with regard to the initial temperature of the gear before the test.

Tables 1 and 2 illustrate that both gears exhibited temperature variations as a function of speed and applied torque. The minimal temperature elevation was 4.22 °C for the bio-composite and 3.99 °C for the green composite. The maximum temperature for the bio-composite gear was 36.82 °C, which exhibited a temperature variation of 771.66% after tripling the initial rotation speed of 500 rpm and multiplying the initial torque of 2 Nm by five. Conditions of 10 Nm and 1500 rpm produced the maximum temperature of the bio-composite; the gear that used the green composite broke prematurely during the test.

Because the green composite gear failed prematurely, we cannot evaluate the temperature or quantify the endurance of this gear. This gear is not useful at the maximum torque and speed that were considered in this study.

Table 1
Temperature increase for bio-composite gears under various operating conditions.

Bio-composite	Speed [rpm]		
Torque [Nm]	500	1000	1500
10	20.55	23.38	36.82
6	10.39	15.98	19.64
2	4.23	5.03	7.90

Table 2
Temperature increase for "green" composite gears under various operating conditions.

"Green" composite	Speed [rpm]		
Torque [Nm]	500	1000	1500
10	20.47	25.15	–
6	11.53	17.18	19.30
2	3.93	4.87	7.36

In the bar graph in Fig. 7, the temperature values for both gears are grouped by the rotational speed. The colors in this graph indicate the different torque values that were applied. The external bars indicate the bio-composite gear, whereas the inside bar indicates the green composite gears, which enables a direct comparison.

A direct comparison of the working temperatures revealed the existence of at least one major difference in the damage characteristics of the bio- and green composite gears. The major difference was the premature breakage under the extreme conditions of the test, i.e., 1500 rpm and 10 Nm.

As shown in Fig. 7, the torque had a major influence on the working temperature, and its effect was independent of the material used. Micro-defects and micro-misalignment could have contributed to the maximum difference in temperature that was observed in both materials (1.77 °C, when measurements of both materials could be obtained). This maximum difference occurred at 1000 rpm and 10 Nm. The bio-composite had a slight tendency to exhibit slightly higher temperatures, which can be easily observed in the 1000 rpm series, in which the increase in torque had a greater effect on the temperature of the green composite. However, this hypothesis is not entirely confirmed, because the trend was not fully observed in the 500 rpm and 1500 rpm series. However, on average, the green composites exhibited a higher temperature of 0.34 °C. In fact, the differences in temperature are sufficiently small to be attributable to the measuring system (e.g., minor misalignments of the gears). At this point, it is not possible to state that there is a significant change in temperature behavior between the two composite options. For this conclusion to be considered true, data from the extreme operating condition test must be excluded because the green composite suffered premature failure.

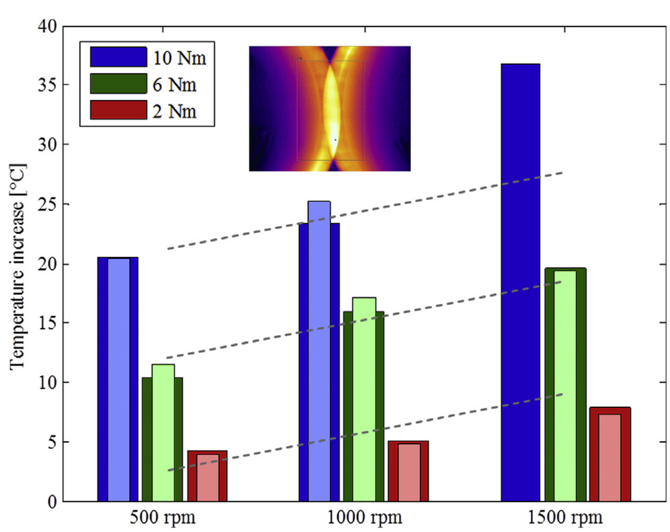

Fig. 7. Comparison of the variations in temperature for the "green" and bio-composites. The results for the bio-composite are represented by the wider bars, and the results for the "green" composite are represented by the narrower bars.

Although the operating temperature increased with torque and speed in Fig. 7, the torque had a major influence over the speed: if the speed increased, the heat generation increased because of an increase in the tooth sliding speed. However, the air convection coefficient also increased with the rotational speed. The slight increase in the temperature with the rotation speed indicates that the increase in the convection coefficient was not sufficiently high to fully compensate for the increase in the frictional heat generation. Considering that the behavior of both materials are the same, all of the temperatures can be used to construct an approximate model of the behavior using bi-linear interpolation (the data corresponding to 1500 rpm and 10 Nm were excluded from the calculations for the reasons noted above). The model has the following form:

$$\Delta T = a_t + Torque\ [Nm]*b_t + Speed[rpm]*c_t \tag{1}$$

where the resulting coefficients are: $a_t = -5.19$, $b_t = 2.32$ and $c_t = 0.6.38\text{E-}3$. The models result in a coefficient of multiple determination (R^2) that indicates that 97.26% of the results are explained based on the given variables. The dashed lines in Fig. 7 represents the results of the model for the three different levels of torque.

In terms of the temperature behavior of both composite gears, the temperature increased nearly linearly with increasing torque, with some offset when the rotation speed changed. This condition is consistent with the theory of frictional heat generation. However, the only exception was the extreme maximum point of the torque and speed. This point exhibited an increase in the temperature that was not proportional with the other increases, which indicates that another mechanism of heat generation might have been activated under these severe conditions. For example, this alternate mechanism could be an excessive deformation of the tooth profile by either contact pressure or tooth bending. In either case, the result would be that the contact would not occur according to the original involute profile, greatly increasing the sliding speed and heat generation.

In summary, the behavioral trends involving temperature for the green composite gear were highly similar to those of the bio-composite gear. However, the figure indicates that a significant change occurred under the conditions of 10 Nm and 1500 rpm. This point corresponds to an abnormal temperature in the bio-composite gear. Under these conditions, contact could have occurred from excessive contact pressure or tooth bending, which could have increased kinematic effects during meshing and led to tooth rupture. The rupture of the green composite at this situation can be explained by the fact that the laboratory characterization of the NPE itself demonstrated that the material is less resistant to dynamic forces and thus was more fragile. In a previous experiment [31], monotonic tensile testing demonstrated that the polymeric matrix strain limit of pure PE could not be found because this limit exceeded the tensile machine's testing limits. A sudden rupture was detected at 7.80% strain for the matrix alone in the NPE during tensile testing, indicating a difference in ductility compared to the traditional material. This condition involving a detectable difference between both gears operations is termed the "severe" operating condition.

3.2. Thermo-mechanical modeling

One important step in the development and study of these new gears is to verify how they behave compared to other materials from the literature. There have been a number of experiments on spur gears using conventional engineering plastics for similar tasks [38,39]. However, not all these experiments with real plastic gears were performed using the same gear configurations. Thus, using values of rotational speed and torque are not meaningful for comparison. For example, for two gears rotating at the same speed with the same torque applied, the local sliding speed and pressure applied to the active flanks will be different if one has a pitch diameter two times greater than the other. For comparison, the geometry of each gear from the literature must be considered, and the values of speed must be converted into universal tribological values of pressure and mean average sliding speed. Tsukamoto [40] developed a set of equations for tribological values of equivalent Hertz pressure (P) and average sliding speed (V) for gears:

$$P = \left\{ \frac{4T_1}{\pi b} \frac{E'(N_1 + N_2)}{N_1^2 N_2 m^2 \sin\phi \cos\phi} \right\}^{1/2} \quad (2)$$

$$V = \left\{ C_x \sin\phi_x - \frac{(N_1 + N_2)}{N_2} \sqrt{R_{O2}^2 - R_{b2}^2} \right\} \pi\omega_1 \quad (3)$$

Where

$$R_{O2} = \frac{N_2 m}{2} + Xm + m \quad (4)$$

$$R_{b2} = \left(\frac{N_2 m}{2}\right) \cos\phi \quad (5)$$

$$\frac{1}{E'} = \frac{1 - \upsilon_1^2}{E_1} - \frac{1 - \upsilon_2^2}{E_2} \quad (6)$$

In the indices, the subscript 1 indicates the driving gear, and the subscript 2 indicates the driven gear. E is the material's Young's modulus, C is the center distance between gears, N is the number of teeth, T is the applied torque, ϕ is the pressure angle (rad), ϕ_x is the operating pressure angle (rad), and ω is the rotation speed (rpm). X is the profile shift coefficient, which is considered zero. In this case, the pressure angle and operating pressure angle have equal values.

A summary of all important gear characteristics evaluated in this study is shown in Table 3, including the tested gears and the configurations from the literature. As stated above, comparisons of newly developed composites with those currently used for particular applications are particularly important. The goal is to replace plastic gears with an equivalent ecological solution. Plastic gears are often made with engineering plastics, i.e., plastics that have a superior Young's modulus and tensile strength that can transfer the load and maintain accuracy during gear meshing [31]. The most widely used engineering plastics in gears are nylon (PA66) and acetal (POM) [13,41,42]. The performance of the developed composite gears during application is compared with studies of plastic gears from the literature to ensure the applicability of the newly developed gears.

The first reference (termed "reference 1") is Mao [39]. In the original work, Mao studied the link between surface wear and temperature. He measured the external surface temperature on acetal gear pairs at different rotational speeds and applied torques. Both gears were identical and made of plastic. Another interesting study is the work of Yakut, Düzcükoğlu [38] (termed "reference 2"). In a similar manner, they analyzed the gear damage experimentally with various rotational speeds and torques using various parameters, including external temperature. However, these authors used a less commonly used plastic gear, i.e., a plastic pinion made of PC/ABS with a metallic gear. PC/ABS combines the greater heat resistance of polycarbonate with the improved processability of ABS [43].

This equation is valid only at reasonable levels of gear damage. At a certain point, the pressure and temperature of yield an involute profile of the gear; in this manner, the heat generation is increased, which will lead to more damage and heat generation. This is highly auto-destructive process was discussed in numerous papers [6,31,44]. It has the characteristic of increasing the dynamic loads and temperatures in non-proportional manner. It is highly likely that the most severe condition of the bio-composite was at this stage; under the same conditions, the green composite gear failed prematurely. Thus, this point will not be considered for a linear approximation. That dataset comprises experimental measurements obtained from our testing and data available from the literature (Table 4).

The simplest and classical model used in the temperature and PV estimation combines these two variables into one: the product

Table 4
Normalized P and V characteristics with increasing temperature.

Bio-composite				
V [m/s]	18.34	36.67	50.01	
P [MPa]				
65.82	4.2	5.0	7.9	
114.00	10.4	16.0	19.6	
147.18	20.5	23.4	36.8	
"Green" composite				
V [m/s]	18.34	36.67	55.01	
P [MPa]				
66.48	3.9	4.9	7.4	
115.14	11.5	17.2	19.3	
148.65	20.5	25.2	–	
PC/ABS with metal gear [38]				
V [m/s]	39.46	52.61	78.92	
P [MPa]				
37.08	22.0	29.0	35.0	
41.94	25.0	32.0	44.0	
50.12	27.5	42.0	53.0	
Acetal [39]				
V [m/s]	15.34	30.67	46.01	76.68
P [MPa]				
37.60	10.0	3.0	7.0	35.0
53.17	66.0	63.0	55.0	77.0
66.66	80.0	77.0	84.0	112.0
77.84	98.0	95.0	112.0	–

Table 3
Gear characteristics.

Material	Bio-composite	"Green" composite	PC/ABS with metal gear [38]	Acetal [39]
M (mm)	2.54	2.54	3.5	2
E (GPa)	4.48	4.57	2.12	3.12
N (N1 = N2)	20	20	26	30
f (mm)	6.35	6.35	14	30
alpha (deg)	20	20	20	20

Table 5
Results for PV interpolation.

Coefficients values	Bio-composite	"Green" composite	PC/ABS with metal gear [38]	Acetal [39]
a_l	3.17E-03	3.26E-03	1.18E-02	1.29E-02
b_l	2.35	2.26	5.40	33.71
Correlation (R^2)	0.54	0.51	0.93	0.28

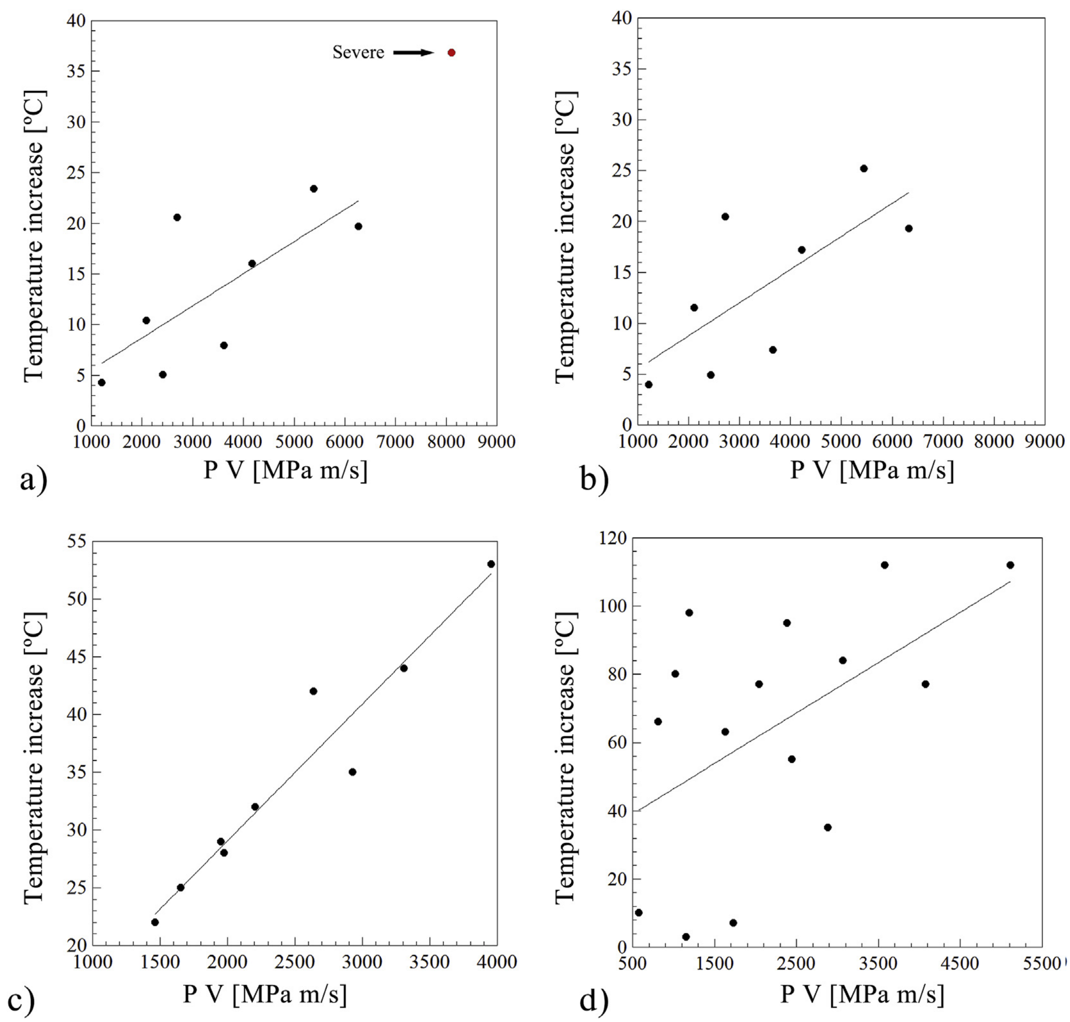

Fig. 8. Raw data and results of 1D interpolation for the four compared cases: A) PE bio-composite, b) PE "green" composite, c) reference 1 [38], and d) reference 2 [39].

PV. Some authors have estimated the temperature increase is a linear function of PV [45]. The results using this classical approach are shown in Table 5 and graphically illustrated in Fig. 8. The severe operating condition was excluded from the bio-composite calculations for the reasons noted above. This point is, however, still represented in Fig. 8a by a red dot. Fig. 8a, b and d illustrates that there are few correlations between PV and the increase in temperature. The raw data are highly scattered and do not follow a given trend. This lack of a strong correlation is numerically verified with the correlation coefficients of 53.60%, 51.36% and 28.10% for the results of the bio-composite, "green" composite and acetal gear, respectively. An exception is found for PC/ABS, where a correlation of 93.00% was obtained; this correlation is visible in Fig. 8c. This gear is the only mixed set, i.e., it is a plastic gear meshing with the metal gear. The fact that the metal gear has a thermal conductance that is considerably higher than that of plastic could have an effect because the majority of the heat generated on the surface is transferred to the metal gear [13]. This approach is not the best suited for the sets of gears made of ecological composite materials.

$$\Delta T = a_l * PV + b_l \quad (7)$$

Thus, another model that is consistent with the theory of plastic gearing is proposed. It is possible to hypothesize that the temperature will increase nearly linearly with the contact pressure and sliding speed. Thus, we propose the following approximation:

$$\Delta T = a_d + b_d\, P + c_d\, V \quad (8)$$

The results from the regression and the proportion of the variance explained by the model are listed in Table 6. The model appears to accurately represent the experimental data. In the case of our experimental measures, the model explains more than 97.2% of the data. A similar but lower value of variance explanation is found

Table 6
Results from the temperature increase interpolation.

Coefficients values	Bio-composite	"Green" composite	PC/ABS with metal gear [38]	Acetal [39]
a_d	−14.84	−15.80	−32.56	−85.21
b_d	0.22	0.23	0.94	2.31
c_d	0.17	0.16	0.47	0.43
Correlation (R^2)	0.97	0.98	0.93	0.93

in the literature data, i.e., more than 92.7% in the case of PC/ABS and 92.6% in the case of acetal gears. The lower correlation of the acetal gears might indicate different behavior. In fact, acetal and nylon gears are often modeled using a model with only one coefficient for the product of P and V [45], which will be discussed further. After proceeding to the raw data treatment and bi-linear regressions, a graphical visualization of the experimental data and the approximation can be observed in Fig. 9. This 3D graph shows the data used in the horizontal axis of P and V with a vertical axis of the increase in temperature. In this figure, a general increasing trend is observed for temperature with increasing sliding speed and local pressure. Changes in the intensity of the slope or the influence of the variable are notable on a case-by-case basis. This can be numerically analyzed using the results of Table 6. In fact, these results are meaningful because this approximation can assess the reaction of the plastic gear set to changes in P and V.

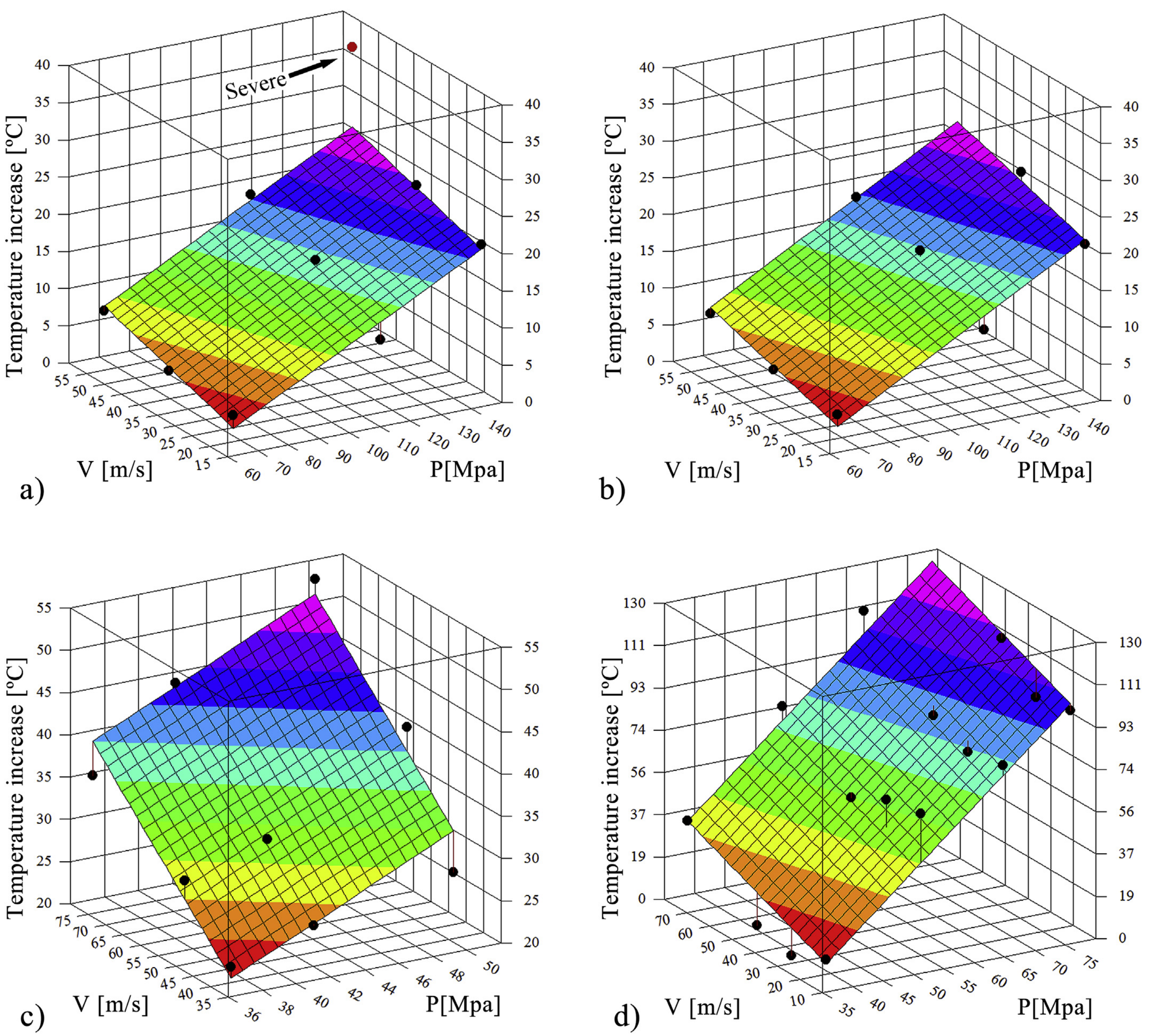

Fig. 9. Raw data and results of 2D interpolation for the four cases: A) PE bio-composite, b) PE "green" composite, c) reference 1 [38], and d) reference 2 [39].

In our model, the "b_d" value indicates the influence of local pressure, where "c_d" is the influence of the average sliding speed. In the first analysis of the results, they are all the same order of magnitude. The b_d value of the green composite is slightly higher than that of the bio-composite. However, the value of the PC/ABS is approximately twice that of the proposed ecological options, indicating the higher sensitivity with increasing loads. More specifically, PC/ABS is 336.6% more sensitive to the P value than the bio-composite and 312.5% more sensitive than the "green" composite. The acetal set working temperature is more than nine times more sensitive to an increase in load than the ecological composite options. More specifically, acetal is 145.4% more sensitive than PC/ABS to the parameter P.

The results are different in terms of the influence of speed on the temperature. The PC/ABS and acetal solutions were very sensitive to the sliding speed; the c_d values were the highest. The ecological options exhibit approximately the same values of c_d, which are approximately one third of the values of c_d acquired from the non-ecological solutions. More specifically, the value of c_d for the bio-composite is 36.1% of the value of the PC/ABS solution. The values for the "green" composite and acetal are 34.4% and 93.3%, respectively, compared to the same base (PC/ABS).

These results are meaningful because the ecological composites when applied to gears are less prone to thermal damage with a change in the operating parameters.

3.3. Root stress fatigue results

These results can be observed in Fig. 10. The fully removed tooth from the excessive efforts can be observed in the image of the broken gear. Interestingly, a large crack consistently appears in many gear teeth starting at the root of the non-loaded flank. This observation is a known phenomenon in gear damage that is called "premature root failure" [46].

As previously discussed and demonstrated in the photos, the main cause of failure in the ecological composite gears was tooth root fatigue. The gear teeth experienced the power of a transmitted load, so their stress state varied cyclically, which explains their failure to fatigue loading at a level well below the yield strength of the material. In particular, the breaking gears frequently resulted in crack propagation at the root of the tooth because of flex fatigue. Comparing these results with those from the literature produces some interesting findings. The results from the work of Senthilvelan and Gnanamoorthy [47] are used for this section. In this study, the authors studied the bending fatigue limits of gears that were composed of Nylon 6. Interestingly, the authors also compared the utilization of glass fiber-reinforced gears. As in the previous sections, conducting comparisons is not convenient in terms of the applied torque but instead in terms of the flexural stress at the tooth root. The equation of [48] should be used to obtain the equivalent root stress and perform a suitable comparison:

$$\sigma = \frac{FP}{bY} \tag{9}$$

where σ is the root stress in psi, b is the tooth width in inches, F the tangential force in pounds and Y is the Lewis form factor.

The results are shown in Fig. 11. The ecological composite gears behave similarly to the Nylon gears in terms of fatigue. In Fig. 11a, the range of the test gears (500–1500 rpm) is consistent with the results from the literature (i.e., 600 to 1200 rpm). For better visualization, the results from the experiment and from the literature are available at the same speed of 1000 rpm. The results are shown in Fig. 11b. All the results exhibit logarithmic behavior in accordance with the theory of fatigue.

The best material is the bio-composite gear, especially for high stress levels. At 36.65 MPa, the gear underwent 40,485 cycles, whereas at the same amount of stress, the "green" composite underwent only 4172 cycles. This is a symbolic gap because the "green" composite resisted 89.69% fewer cycles than the bio-

Fig. 10. Prematurely broken "green" composite gear.

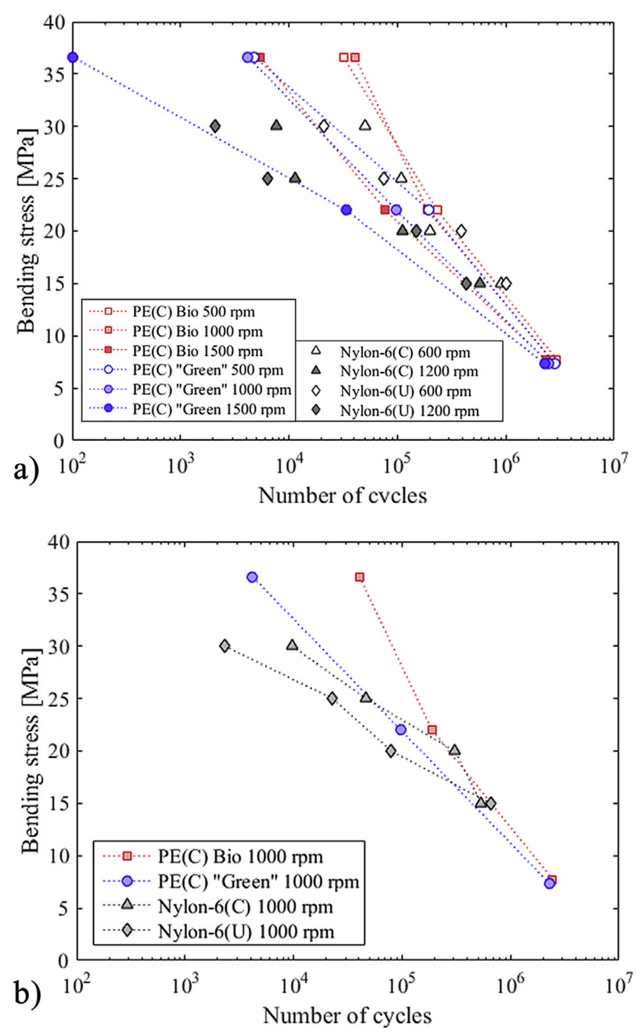

Fig. 11. Root fatigue resistance comparison of ecological composite gears and nylon 6 gears. Regarding the notation in parentheses, C indicates a composite material, whereas U represents a non-composite material.

composite counterpart. This result is likely related to the fact that at high stress levels, the resulting dynamical forces on the teeth are also the highest. Because the "green" matrix is more fragile, it can absorb less such impacts.

The difference is lower for a stress level of 21.99 MPa. The bio-composite underwent 188,968 cycles, whereas the "green" version underwent 97,524 cycles, i.e., a difference of 48.39%. This decrease in the difference is consistent with the "green" matrix not effectively supporting dynamic forces. The decrease in bend stresses will result in lower dynamic forces and a lower impact on each tooth, and thus, the difference between materials should decrease with moderate stresses. The applied bending stress from the extreme case to the last case decreased by 40%, and the gap between the materials dropped by 41.30%, suggesting a relationship.

In the case of the lowest applied stress, i.e., 7.33 MPa, no damage to the gear was observed during the duration of the test. No signs of cracking or even surface wear, indicating a low friction coefficient, were observed. If a rupture occurred in the teeth, it would result in a lower difference between materials because the static mechanical properties of both are highly similar. The continuous line toward the maximum value of the horizontal axis indicates the estimates of the fatigue behavior at low stress for the ecological composite gears.

In this figure, the "green" composite gear and Nylon composite gear exhibit nearly identical behavior with regard to the bending fatigue. Because there is no common stress point in the experiment or the literature, a local linear approximation using the closest two points can be considered for comparison. In this case, the bio-composite and "green" composite at a bending stress of 30 MPa endured 107,881 and 46,544 cycles, respectively. There is a 56.86% decrease in the number of cycles that the "green" composite can endure, again due to its fragile nature. The number of cycles that the nylon-6 composite can endure at the same level of bending stress, which is technically the same amount of fatigue resistance, is of particular interest. These results are useful because they indicate that an ecological solution can potentially have the same resistance as a non-ecological solution currently utilized in demanding situations for plastic gearing. Furthermore, the ecological alternative had a superior performance to that of the pure nylon-6, which is a commonly applied material for plastic gears. Compared with the "green" solution, the number of cycles it could endure was 104.58% higher than, or roughly double, that of an entirely ecological material. If a concession can be made on the ecological side, the bio-composite proposition withstood 374.18% more cycles, or nearly four times as many cycles, at the same root stress. This indicates that the practicability of ecological gears compared to current solutions is promising, and further analyses must be performed. It is important to note that in the ecological gear testing, the test was stopped when the gears reached $2 * 10^6$ cycles. When the gears were examined, no signs of wear or imminent fatigue fracture were observed.

3.4. Fatigue-temperature relationship

In this study, we also investigated whether there is a correlation between operating temperature and the number of cycles until failure. The results are shown in Fig. 12. The relationship is linear with the exception of the point with maximum torque and maximum rotating speed of the bio-composite. This is another confirmation that at these operating circumstances, the gear reached the phase of severe damage. The other points were considered for a linear regression of the following form:

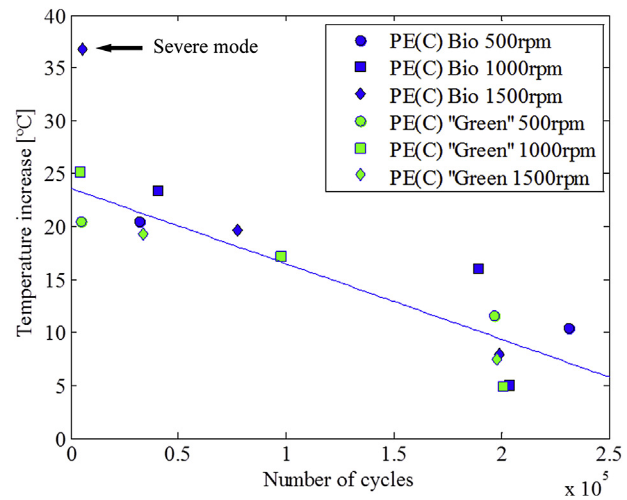

Fig. 12. Relationship between the operating temperature and the number of cycles for ecological composite gears.

$$\Delta T = d_f * N_{cycles} + e_f \quad (10)$$

The results of the regression indicate that the coefficient d_f has a value of $-7.14*10^{-5}$ and that e_f has the value of 23.63. This model explains 81.24% of the variance. The point of severe damage for the bio-composite gear was not considered for the regression (bio-composite, 1500 rpm, 10 Nm). In this case, the gear was in a severe damage phase, which indicates that non-negligible interactions occurred between damaging modes. The exclusion of this point is consistent with the modeling of the thermo-mechanical behavior.

The temperature and numbers of cycles to rupture have some correlation, and the proposed model suggests that the severity of operation will increase the temperature and decrease the number of cycles to rupture. The incurrence of other variables that affect the operating temperature and fatigue life must be studied. However, the model is still important because it can be useful in cases where the correlation is 80%.

3.5. Acoustic emission results

The majority of studies consider only the final phase of the fatigue process at the root of the tooth, namely, the appearance of the final failure. However, the entire process of fatigue failure of the mechanical elements can be divided into the following steps [49–51]: 1. nucleation of micro-cracks; 2. micro-crack growth; 3. long crack growth; and 4. occurrence of the final failure. In the case of a new material, it is important to study the fatigue development phases.

The release of AE energy in the gear meshing process should be analyzed to verify the phases of gear damage until the final rupture. Three patterns of AE emission energy are found. The first is found in cases of low speed and low torque. In this case, the gear structure is not conducive for transmitting the torque from one gear to another. The evolution of energy until rupture is linear, and no major changes in the trend occur. This pattern is found in the case of 6 Nm and 500 rpm but also for all speeds with 2 Nm of torque. These are the longest tests runs, and because of the length of the test, any change in the behavior is not clearly observed in the AE due to the vibration from the test bench.

A second and more interesting pattern of energy evolution can be found in Fig. 13b. Trends in the slopes of energy evolution can be observed in this case. Interestingly, the changes in the trend are

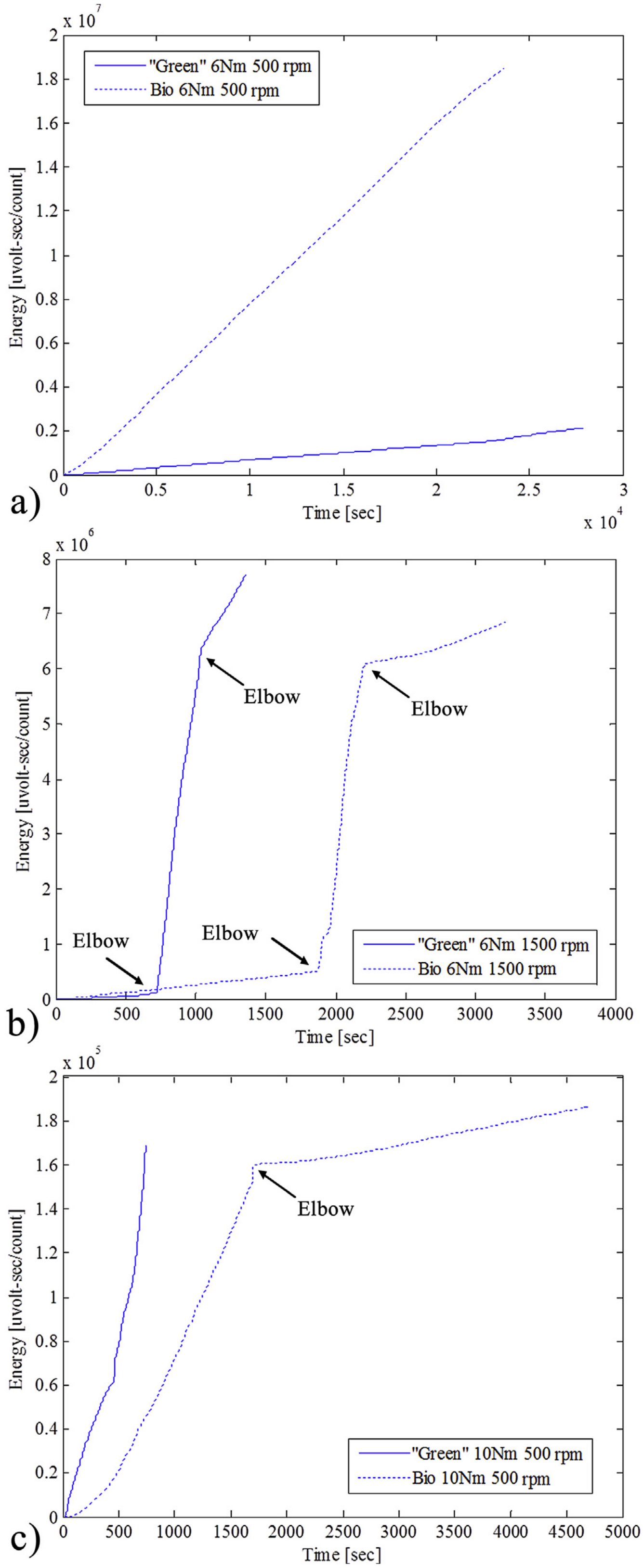

Fig. 13. Energy evolution profiles in various tests.

clear and well delimited. In fact, it is possible to distinguish two clear changes in the trend for both bio-composite and "green" composite gears. This image illustrates that the damaging process has three phases. One initial phase has low energy evolution. This phase is occurs in the case where the fabrication characteristics of the gear are preserved and there is no rapid crack propagation. The AE results indicate that this is likely phase 1 of fatigue, i.e., nucleation of micro-cracks. In the second phase, cracks are seeded and the propagation begins. Because propagation of cracking represents a major internal damage as the structure of the composite separates, this explains the increase in the acoustic emission. This could be attributed to phase 2, i.e., micro-crack growth. The third phase has an energy generation lower than the second phase but higher than the first one. According to the theory of fatigue, this would be the third phase of long crack growth, there was a decrease in the emissivity of AE. This could be explained by the fact that the presence of long cracks would drastically decrease the tooth stiffness, thus reducing some AE generation as the damaged teeth would no longer offer resistance, thereby reducing the vibration. This is an interesting phenomenon, and further investigation is necessary. According to the AE data, once the gear tooth is damaged, it will work for few cycles until the final rupture occurs.

This pattern was observed in the case of a torque of 6 Nm for speeds of 1000 and 1500 rpm. The third pattern occurs when high torque is applied. This is similar to the last phase, with the difference that there is no third phase of damage or it is excessively short, indicating that if one tooth lost its resistance due to the presence of long cracks, the entire gear cannot sustain such high levels of stress in this operation. Thus, the third phase prior to the final rupture is extremely short.

One important conclusion is that when no significant internal defects are observed (Fig. 13a), the green composite releases acoustic energy in a much lower rate. This finding is in accordance with the acoustic behavior observed at the specimen level in previous studies [16,31]. It was found that the NPE matrix itself is less prone to emit perceptible acoustic signals. Furthermore, it was observed that the NPE matrix is more fragile; thus, it can endure fewer cycles at the same level of applied stress during fatigue testing, leading to the formation of a long crack earlier than the bio-composite (as can be observed in Fig. 13b). At this point the material will progress faster toward final rupture and the internal movement and friction on the material under internal separation will inevitably emit a much higher acoustic energy as a result of the lower internal integrity. This proposed mechanism explains why at higher torque and speeds a gear constructed from material that emits less acoustic energy appears to be emitting more acoustic energy: it is fact the onset of large cracks and a change in the phase of the damaging process taking place earlier because of the lack of material tenacity.

4. Conclusions

In this article, new ecological sets of plastics gears were proposed for the replacement of traditional non-ecological plastic gears. It was possible to compare the behavior of such ecological gears in terms of fatigue and operating temperature with commonly used materials for similar applications. The results indicate that the operating temperature of these gears increases with the mean contact pressure and average sliding speed. The semi-ecological bio-composite gear and fully ecological "green" composite gears behaved similarly with regard to the operating temperature. More interestingly, they are less prone to an increase in operating temperature with an increase in pressure than non-ecological materials.

Additionally, the ecological gears exhibited comparable behavior in terms of fatigue than commonly used nylon gears. In this case, there was a noticeable difference between the behavior of the bio-composite and the "green" gear. The bio-composite gear had a superior performance, even better than nylon reinforced with glass fiber. This can be attributed to the ductile characteristics of the PE matrix. The NPE matrix was notably more fragile and offered less resistance to fatigue during gear meshing. Nevertheless, the resistance was highly similar to the nylon-reinforced with glass fiber and superior to the pure nylon gear.

The EA of the experiment indicated that the theoretical phases of fatigue can be observed by the AE instrument during operation. The changes in the phases of fatigue are visible with clear changes in the tendency of the energy readings. An increase in the energy rate with micro-crack propagation occurs after an initial stable phase of crack nucleation. A third phase that is likely linked to the onset of substantial reduction in the tooth stiffness that leads to the final failure. It has been demonstrated that the fully ecological gears are feasible and can replace traditional materials, such as engineering plastic, in a low-cost manner. Longer endurance testing to determine the limit of failure under the wear mode is recommend for further investigation because in this testing no wear was observable at the tooth level for the non-failed gears.

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