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TRIBOLOGICAL BEHAVIOR OF PLA BIODEGRADABLE MATERIALS USED IN THE AUTOMOTIVE INDUSTRY

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Abstract: The use of biodegradable thermoplastic materials with applicability in various industries such as automotive, consumer products, medical equipment and others has increased considerably in recent years. This increase in demand for biodegradable materials is closely linked to the growing concerns of producers and consumers alike, especially with a view to replacing, on a large scale, synthetic and non-biodegradable polymeric products. This paper presents the performance of biodegradable polymers PLA, HD PLA Green and Impact PLA Gray in terms of tribological properties, the coefficient of friction, wear and their behavior in different climatic test conditions on equipment that simulates the operation of the worm-worm wheel assembly that is part of the drive mechanism of the car wipers. The highest average value of the wear coefficient and of the wear track depth was recorded in the case of Impact PLA Gray sample followed by HD PLA Green and PLA. Regarding the results of the simulation of the operation within normal gear parameters of the worm-worm wheel (the worm wheel made from the materials proposed for this study), it was found that the mechanism ensures normal operation only for negative temperatures of use, -10°C being the temperature set as a standard in the simulations. For the other climatic conditions, i.e. higher temperatures (18-30)°C, the worm-wheel is not suitable for use.
Key words: PLA, biodegradable material, COF, wear, worm wheel.

1. INTRODUCTION

Recently, the need for an innovative, intelligent and sustainable biodegradable plastics industry with various areas of applicability has increased considerably. Thus, a design and production that fully respect the needs of reuse and recycling are pursued, which significantly contributes to reducing greenhouse gas emissions, mitigating pollution and reducing global dependence on fossil fuels. Given this need for sustainable raw material resources and the environmental problems caused by non-degradable plastics, car manufacturers are always looking for new materials with little impact on the environment, which ensure functionality comparable to that of materials commonly used in the automotive industry, [1, 2].

Most biodegradable thermoplastic materials are based on natural raw materials (monomers), natural polymers, such as cellulose, starch, polylactic acid, keratin or even hydrocarbon resources. These natural raw materials are more or less biodegradable, but they have the advantage of being sourced from renewable resources and therefore they will always be available. However, natural polymers are not thermoplastic. To achieve this property, materials are usually processed in combination with a plasticizer. Of course, the biodegradable properties of a suitable plasticizer must be taken into account when selecting it, [2].

Polylactic acid (PLA) is a biodegradable thermoplastic polyester obtained from renewable resources such as corn starch, tapioca roots, cassava, sugarcane or sugar beet pulp. It is also the most widely used biodegradable material in 3D printing, being very easy to print on, available in a wide variety of colours and has functional characteristics similar to those of polypropylene, polystyrene or polyethylene, [3]. The other types of polylactic acid, HD PLA Green (after thermal annealing treatment, it will have high impact resistance and high temperature resistance) and Impact PLA Gray (it has high impact resistance) were obtained by adding a biodegradable polymeric material to increase certain functional properties of the material (such as impact resistance), [3, 4].

The biodegradable materials used, studied in this paper, were PLA, HD PLA Green and Impact PLA Gray, materials produced by the Fiberlogy company, the wire having a diameter of 1.75mm, [3]. The process parameters applied during the printing of the worm wheels, used throughout the car wipers, were as follows:

- PLA wheel (Fiberlogy, printing temperature 190°C, heated bed 50°C, nozzle diameter 0.4mm, deposited layer thickness 0.15mm);
- PLA HD wheel (Fiberlogy, printing temperature 210°C, heated bed 50°C, nozzle diameter 0.4mm, deposited layer thickness 0.15mm);
- Impact plate PLA Gray (Fiberlogy, print temperature 230°C, heated bed 65°C, nozzle diameter 0.4mm, thickness of layer deposited 0.15mm).

A Tiertime UP 2 mini printer is the equipment used to print the abovementioned parts, by means of the Fused Deposition Modeling (FDM) method.

The Discovery ATC DM600 thermostatic climate chamber was used to simulate the environmental conditions in which this equipment is designed to operate.

The coefficient of friction and wear was measured with a T-11 Elevated Temperature Pin-On-Disk Testing Machine for Tribotesting of Lubricants and Engineering Materials, with the sample size of 20x20mm, the data being analyzed using the Alicona-IF software package. -MeasureSuite.

2. EQUIPMENT DESCRIPTION AND OPERATION

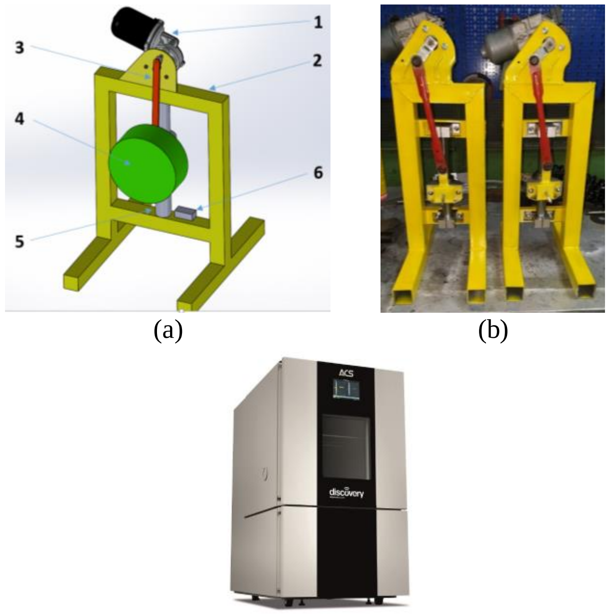
The equipment proposed in this paper simulates the car wiper mechanism, which also includes a worm-worm wheel assembly. The sample printed from biodegradable materials for the purpose of determining its behavior during operation was the worm wheel. Another purpose pursued was the experimental validation of the proposed model, of course taking into account the meteorological and climatic conditions in our country. Thus, due to its temperate continental climate, Romania has between 100 and 200 days with precipitation each year, [5]. In order to validate the worm wheel model, an estimated number of 150 days of precipitation was considered.

We considered, from the very beginning of the simulations, that atmospheric humidity and solar rays have no influence on the tests because the assembly works in a thermal chamber, watertight and without access during use.

Tests were carried out using two similar pieces of equipment from the kinematic and constructive points of view. The first equipment was used to test the operation of the nylon worm wheel, while the second equipment was used to test the operation of the worm wheels made from the biodegradable materials mentioned above within the worm-worm wheel assembly.

At the end of the test period, the wear due to friction was determined in the presence of a mineral-synthetic lubricant used in the gear, SKFLGWA 2 / 0.4, grease for high loading loads, high pressure and a wide range of operating temperatures.

The worm wheel (Figure 1(a), Figure 1(b)) is usually made of plastics with low coefficient of friction, [6]. According to the results reported in literature, most of the plastics used very often (PA46, PA6, PA66, PA6E, POM, etc.) have the coefficients of friction between (0.2-0.45). According to the research conducted so far, the coefficient of friction for PLA is 0.11 in the case of translations of a steel ball on the sample surface and 0.12 in the case of material-to-material friction [7], which means lower values than the plastics presented above. The operation was simulated in the Discovery ATC DM600 thermostat climate chamber (Figure 1(c)).



(a) (b) (c)

Fig.1. Equipment for testing the worm wheel made from biodegradable materials: (a) 3D image (1-motor; 2-support frame, 3-crank mechanism; 4-counterweight; 5-linear guide; 6-contactor connected to a counter); (b) image equipment; (c) the Discovery ATC DM600 thermostatic climate chamber

2.1 Establishing test conditions in the thermal chamber

In order to perform the endurance test on the proposed materials, periods with negative temperatures (-10°C) as well as positive temperatures (30°C) were considered.

During the tests, the temperature and the number of days with precipitation were considered, as follows:

√ from the temperature point of view:

-the average annual temperature is 10°C;

-the maximum temperature reached in Romania is (41-42)°C on summer days (July);

-maximum annual average temperature 26.7°C;

-the minimum temperature in Romania may drop as low as -30°C (January), but these values are different depending on the geographical position;

-average annual minimum temperature -6°C;

√ from the point of view of precipitation, the average number of days with precipitation ranges in our country between 100 and 200 days. Thus, the average number of rainfall days is about 150days/year.

The moderate use of a vehicle was considered to be up to 3 hours of daily operation. Considering the average number of 150 days with rainfall, it turns out that, in one year, the car will be used 450 hours (18.75 days/year) in rain, sleet or snow conditions, [8, 9].

Based on the information presented above, the following test plan has been established:

- At 30°C temperature = 32 days/year x 3 hours/day = 96 hours/24 (hours) = 4 working days;

-At -10°C temperature = 35 days/year x 3 hours/day = 105 hours/24 (hours) = 4.375 working days;

-At the average annual temperatures (18°C), depending on the season, geographical region = 18.75 – 4 - 4.375 = 10.375 days = 249 hours/24 (hours) = 10.375 hours of operation.

3. RESULTS AND DISCUSSIONS

The results and discussions in this paragraph will refer to the coefficient of friction and wear determined experimentally for the materials from which the worm wheels were manufactured and to the operating behavior of the worm wheels within the worm-worm wheel mechanism.

3.1 The coefficient of friction and wear for the materials used in the manufacture of worm wheels

For the determination of the friction coefficient (COF), as well as for the determination of the wear of the biodegradable materials studied, 3 samples of each type of material were tested to confirm the stability of the experiments.

Testing conditions for friction coefficient and wear: the test was performed under dry slip conditions, the ball was fixed to the holder and the holder made a circle movement over the square sample, the value of pressing force / applied load was Fz = 49N, the angular speed = 40rpm, wear track radius = 5mm, the testing time t = 900s, the ball has the following characteristics: roughness Ra = 25µm; hardness: 60HRC; diameter = 12.7mm; material: AISI 52100 steel.

In the case of the PLA material, Figure 2, curve (1), an increase of COF is observed in the first 300s, after which the average COF value stabilizes for about 120s, after which it decreases slightly and returns to the value of about 0.0008. For the HD PLA Green material, Figure 2 curve (2) shows a slow decrease of COF during the first 450s, after which a sharp increase occurs, and, at the end of the 900s of the test, the COF value reaches 0.0097. For the PLA Gray Impact samples, Figure 2 curve (3), the COF friction coefficient increases significantly throughout the entire determination, from a COF value of 0.0048 to a COF value of 0.0102. The highest mean friction coefficient, approximately 0.011, was recorded for the PLA Gray Impact sample, followed by the HD PLA Green sample and the PLA sample.

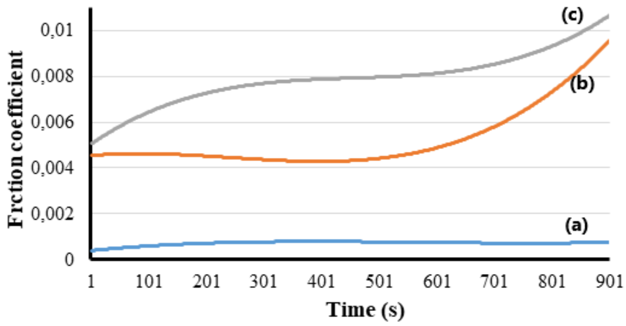


Fig. 2. COF variation with test time for samples from: (a) PLA; (b) HD PLA Green; (c) Impact PLA Gray

The depth of the wear tracks for the studied materials is shown in Table 1, under the aforementioned experimental conditions.

Table 1. Wear depth values for all studied materials

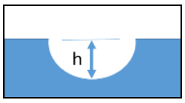
	Sample	Wear Track Depth (h) [µm]	Average [µm]	Std Dev [µm]
PLA	1	15.45	15.5	0.8
	2	14.76		
	3	16.34		
HD PLA Green	1	29.29	29.2	1.0
	2	30.08		
	3	28.17		
Impact PLA Gray	1	48.86	42.1	10.5
	2	47.33		
	3	29.98		

Figure 3 shows the curves of the plastic deformations of the studied materials left by the steel ball during the determination of their tribological behavior.

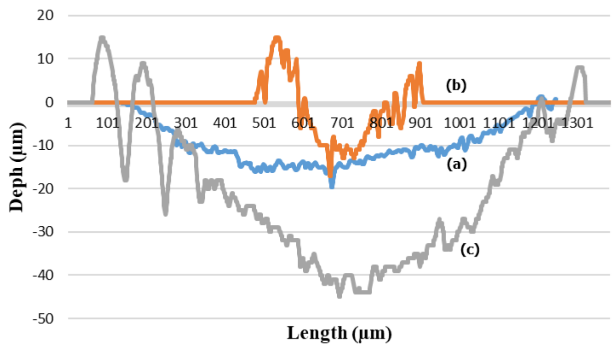


Fig. 3. Average wear variation: (a) PLA; (b) HD PLA Green; (c) Impact PLA Gray

The mean depth value reached by the three wear-tested PLA samples, Figure 3, curve (a), was (15.5±0.8)µm, with a maximum of -14.31µm. In the case of the HD PLA Green material, Figure 3, curve (b), the average depth value is (29.2±1.0)µm, and the maximum depth is close to that of PLA, namely -18µm. The deepest trace was recorded for the Impact PLA Gray material, Figure 3, curve (c), (42.1±10.5)µm, and, regarding the maximum depth reached during the use of the surface, one should note that it was almost four times higher than that of the other 2 materials, -44µm.

During testing the ball is fixed to the holder and the holder makes a circle over the square sample. Thus, Figure 4 shows the images of the wear areas and the recorded variation of the appearance of wear on a certain portion of the ball's trajectory.

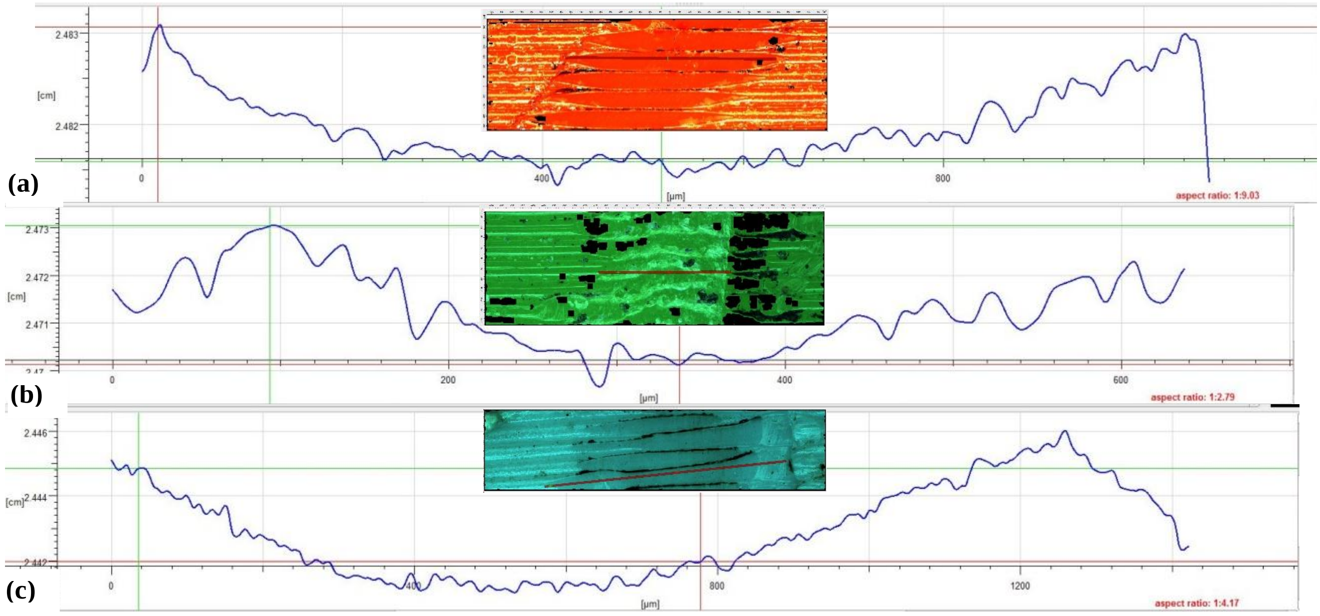
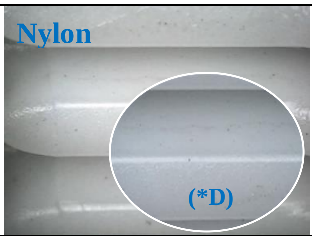
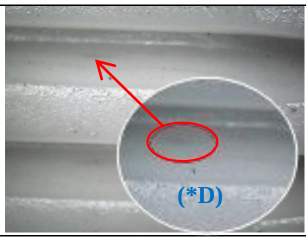
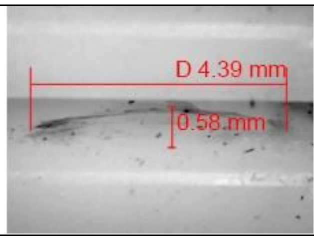
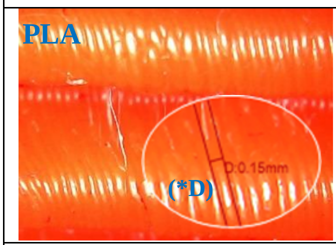
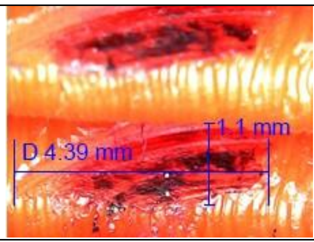
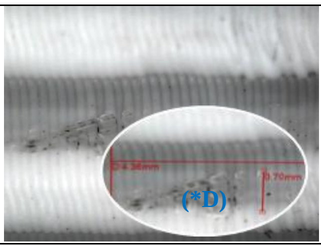
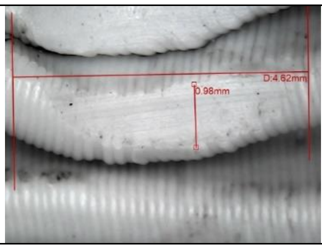
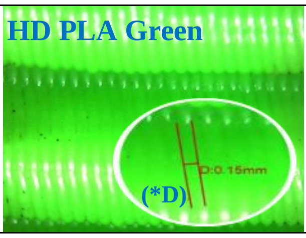
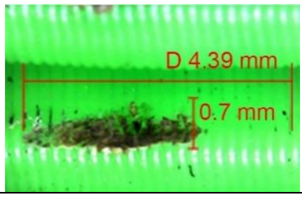
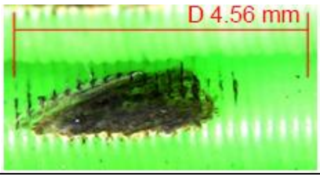
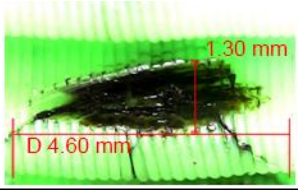


Fig.4. The image of a portion of the used area and the variation recorded at the time of occurrence of wear for: (a) PLA, sample 2; (b) HD PLA Green sample 3; (c) Impact PLA Gray, sample 3

Table 2. Worm wheels from biodegradable materials subjected to wear compared to standard screws from the OEM (Original Equipment Manufacturer) mechanism, *D (detaliu)

Initial appearance of the worm wheel	*After 105 hours of operating at -10°C*	*After 96 hours of operating at +30°C*	*After 249 hours of operating at +18°C*
			
	There is a slight trace of wear / contact stain on the surface, appearance under normal assembly operation conditions.	There is a slight accentuation of the wear under normal assembly operation conditions.	The wear occurs at the end of this operation time, allowing the normal operation of the equipment.
			
	Note the beginning of the wear zone without affecting the normal functioning of the assembly.	There is an increase in the wear area and also the appearance of damaged / burned material. The operation is no longer within normal parameters.	There is a marked wear and a deterioration of the contact area by heat / friction, the operation being outside the normal parameters range.

			
	The appearance of slight traces of wear on the surface, without impeding on the normal functioning of the assembly.	After approximately 12 hours of operation, due to the ambient temperature, the temperature of the gear and the applied load, the material became very malleable with the appearance of plastic deformations that led to the deterioration and destruction of the tooth, the operation being outside the normal parameters range.	No further testing was required.
			
	Note the appearance of small areas of thermally influenced material which did not impede on the operation of the mechanism.	Note the increase of the area of thermally influenced material and, of course, an abnormal functioning of the assembly.	After the operation time, there is also an extension of the thermally affected area and a much more aggravated deterioration of the surface with the absence of normal operating conditions.

3.2 The wear of the worm wheels in working conditions

At the end of the established operating cycles, the worm wheels were reshaped and analyzed microscopically, to show the wear and the condition of the gear.

Thus, for the worm wheels made from the biodegradable materials tested, the behavior of the gear teeth under the preestablished conditions of time and temperature are shown in Table 2.

4. CONCLUSIONS

In general, the biodegradable polymer group PLA, Impact PLA Gray and HD PLA Green shows a much finer wear than other biodegradable polymers such as Pearl BDP Extruder, BDP Flex Extruder, Flex GreenTec Extruder, Fiber Wood, according to previous research carried out by the authors of this paper but not published so far. Also, this group of polymers has low friction coefficients, especially PLA and HD PLA Green.

The shallowest trace of wear was measured in the PLA material with the lowest coefficient of friction, and the worm wheel tested within the mechanism is suitable only at negative operating temperatures -10°C, not being functional at high temperatures of 18°C or 30°C.

The increase of the friction coefficient for the HD PLA Green material resulted in small areas of thermally influenced material, which did not impede on the operation of the mechanism. The operation is within normal parameters for negative temperatures, of -10°C.

The highest coefficient of friction was recorded for Impact PLA Gray material, which obviously also suffered the deepest traces of wear. The worm wheel ensures the normal operation of the assembly only at negative temperatures, of -10°C, the temperature considered as standard in the experiments. At the other temperatures taken into account, the material became malleable with the appearance of plastic deformations that led to the deterioration and destruction of the tooth, the operation being outside the normal parameters range.

5. ACKNOWLEDGEMENTS

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