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THE FUNCTIONAL DEPENDENCE OF THE 3D PRINTED PARTS BY THEIR TRIBOLOGICAL AND THERMAL CHARACTERISTICS

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Abstract: The popularity of bio - based thermoplastic materials with applications in a variety of industries, including consumer goods, automotive, medical equipment, and so on, has grown significantly in recent years. This increase in the market for biodegradable materials is closely related to the growing concerns of both users and industry, especially in relation to replacing the conventional or non-biodegradable polymeric products on a widespread scale. This study examined the tribological performance (friction coefficient) and wear of biodegradable polymers PLA, HD PLA Green, and Impact PLA Gray in various meteorological testing conditions on a simulation stand that replicate the operation mode of worm-worm wheel assembly as part of the drive mechanism of car wipers. The Impact PLA Gray sample had the greatest average value of a wear coefficient and wear resisting during simulation and best on testing. The lowest performance has been recorded by the PLA sample because its melting temperature is the lowest, thus affecting its resistance to friction and wear. Regarding the possibility of practical use of the worm wheel in the proposed assembly, it is recommended only to use at negative temperatures, below -10˚C.

1. INTRODUCTION

Biodegradable materials are adequate alternatives to petrochemical derivatives and have essential roles in environmental protection due to reducing the use of fossil raw materials and decreasing carbon dioxide releases. Therefore, there is an increasing interest in biodegradable materials, which degrade faster than conventional materials. Most biodegradable materials used in sample preparation techniques are biosurphactants, biopolymers and biosolvents, [1].

The development of biodegradable composites based on natural polymers capable of degrading in compounds without danger is one of the priorities in the production of new polymeric materials. The interest in such systems is motivated by the need of using the increasing quantities of synthetic polymers and raw vegetable waste. Moreover, the production of such materials ensures a gradual replacement of polymers synthesizing from oil. This problem can be solved effectively using natural polymers and their compositions capable of degrading under environmental conditions, [2].

In the additive manufacture (Additive Manufacturing-AM) unlike the sub-treatment manufacturing processes, the parts are manufactured layer by layer with a minimum allocation for finishing operations. Because it allows larger savings of materials than traditional processes, 3D printing can be considered a production technology distributed to improve the durability and circular economy worldwide, [3].

Addivative Manufacturing, since the early stage of a single material, is currently going through a huge transition, turning into a multi-material printing, with unprecedented design opportunities. Together with different printing technologies, the manufacture of digital computers - Assisted projects (CAD) for 3D physical objects are achievable in a short period of time. Unlike traditional manufacturing processes, which could only produce a simple geometry, 3D printing has greatly extended the design capacity, [4].

AM is the best method for developing novel materials with exceptional, frequently multifunctional characteristics: printing electronic materials (soft electronics), intelligent materials (such as 4D materials that can change their shape in response to humidity, heat, or other environmental factors), architectural materials (such as materials for cell phones, metamaterial), biomaterials (such as materials for implants, dental applications, tissue engineering scaffolding), biological materials (tissues, organs), and others are examples, with an emphasis on polymers [5].

Among the technologies of additive manufacture, Fused Deposition Modeling -FDM, also known as the Fused

Filament Fabrication-FFF is a low -cost technique using a thermoplastic lament to build layer parts with layer. The popularity of the FDM began with the expiration of Sir Scott Crump's patent from Stratasys and after the Open-Source Reprap project, which has since become the favorite choice of producers. The FDM process is known more popular as 3D printing and belongs to the material of extrusion of materials according to ISO/ASTM terminology, [3].

The present paper aims to highlight the main limitations in operation of the parts made of biodegradable polymerics obtained by using the additive manufacturing - 3D printing, FDM method. The current study consists in the recommendation of substitution of conventional polymers with biodegradable polymers, in industrial applications, for certain conditions. Specifically, in this case it is desired to replace the worm-worm wheel assembly the car wiper mechanism.

2. AM - THE MAIN STRENGTHS AND WEAKNESSES

⮙ The following are only a few of the technological advantages it has over conventional manufacturing techniques that have propelled it to the fore of scientific, commercial, and public attention:

⮙ Geometric freedom, unrestricted complexity, ability to produce intricate parts that cannot be produced using conventional manufacturing techniques, ability to produce new and improved designs with fewer and lighter components, reduced assembly requirements, and the ability to print materials with various properties for novel features;

⮙ Production flexibility: quick prototyping, easy design adjustments (no new equipment required when the design is modified), great for custom parts, easier production process because complex parts may be printed in separate sections; process that is more flexible (less configuration time, quicker assembly, fewer production steps, etc.);

⮙ Resources can be used more effectively when they are printed on demand, produced close to the user, printed on-demand, transported less, and transported for less money.

⮙ The efficiency of the material: durability, the material is used as necessary, fewer waste of materials; low weight, new materials, lower fuel consumption;

⮙ New business models: prototype; shorter launch time; small series; personalized parts; simplified supply chain, [5].

The AM weaknesses include:

⮛ Small scale production: it is not designed for mass production, because traditional manufacturing methods work faster at lower costs and produce better material quality;

⮛ Limited understanding of the processes and materials, including poorly described material qualities, unrecognized processing factors, and absence of quality control standards.

⮛ Irregularities: reduced mechanical qualities caused by flaws and anisotropy; rough surface quality; variability in material properties and printed polymeric part size; dependence on manufacturing procedures;

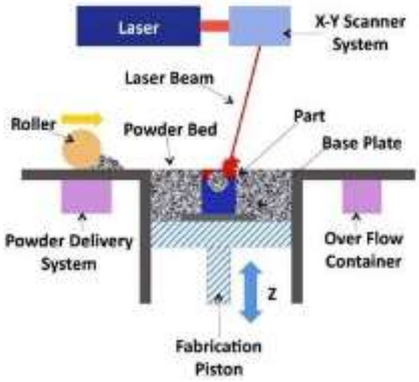
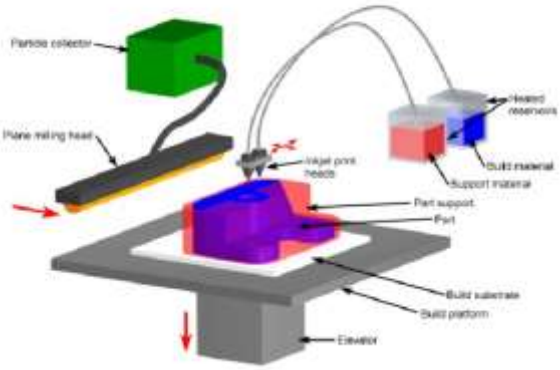
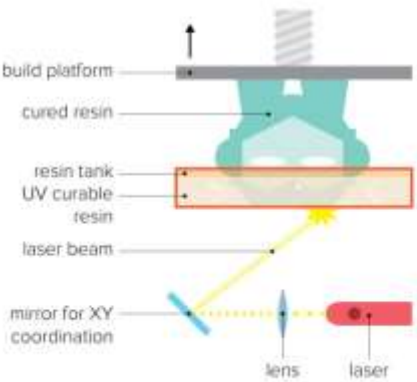
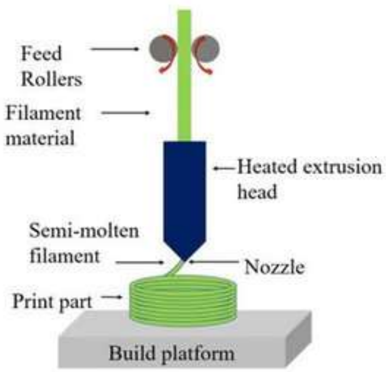
⮛ Cost: pricey high-quality printers; slow deposit speed (raising these speeds is physically impossible); requirement for post-processing; greater expenses for high output; [5];

There are numerous interesting opportunities for research and development in the field of additive manufacture. They refer to:

- high speed printing, which uses volume-based printing rather than pixel-based printing, as well as the discovery and development of high speed processes that produce printed parts of excellent quality;
- materials: connections between processes and materials for additive manufacturing, the search for new materials (with novel chemistry and microstructures), the control of material properties, and predictions about the characteristics, performance, and longevity;
- designs that involve new shapes and new materials for improved multifunctional performance;
- inventions of new technologies AM and new printers capable of printing high quality parts, a wider range of size, multimaterial systems and a wider range of AM materials;
- recycling: increased use of recycled materials, effects of powders' reuse;
- energy consumption of AM processes: evaluation and optimization;
- in situ detection techniques for detecting and correction of material defects during processing;
- production models for AM technologies;
- The comparison between AM and the traditional technologies: materials, equipment and costs with the labor, deposit speed, volume, quality of materials, surface finishing, residual stresses, [5].

Table 1 presents four common AM methods used for polymers and summarizes their advantages and disadvantages. It also lists the representative polymers used in these processes, [5].

Table 1. Advantages and limits of the most used fast prototyping technologies, [5-9]

<table>
<tr><th>Process</th><th>Description</th><th>Advantages</th></tr>
<tr><td>Powder Bed Fusion -PBF

</td><td>• A roller or blade is used to deposit a thin layer of powder on a construction plate;
• The laser merged certain areas of the powder;
• The construction plate is lowered with the height of the powder layer;
• Repeat steps 1–3 for the height of the piece;
• Excess powder is removed.</td><td>- the excess of powder serves as a support, so no support structures are required;
- superior mechanical properties.
Disadvantages
- expensive, large material waste;
- few compatible materials;
- rough or granulated surface.</td></tr>
<tr><td>Used materials</td><td colspan="2">Polystyrene, polyester, polyamide 11 and 12, polypropylene, polyurethane, polyetretercetone</td></tr>
<tr><td>Material Jetting

</td><td>• The liquid polymer is sprayed on a building plate;
• The ultraviolet source (UV) strengthens the polymer;
• The construction plate is lowered or the print head is raised with the height of the drop layer;
• Repeat steps 1–3 for the height of the piece;
• The support material is removed.</td><td>Advantages
- manufacture of multimaterial parts;
- reduced residual voltages;
- high dimensional precision.
Disadvantages
- weak mechanical properties;
- adverse effects on the environment.</td></tr>
<tr><td>Used materials</td><td colspan="2">acrylates, acrylics, polylactics (PLA), epoxy, starch</td></tr>
<tr><td>Vat Photopolymerization

</td><td>• The build plate is positioned on top of a photopolymer vat;
• The UV source under the tank hardens certain areas in a thin layer that contacts the build plate;
• The construction board is raised by the thickness of the hardened layer;
• Repeat steps 1–3 for the height of the part;
• The backing material is removed.</td><td>Advantages
- high resolution build time report;
- good durability;
- it can produce multi-material parts, but it is difficult;
Disadvantages
- relatively expensive due to the need to change the tub;
- requires support material;
- parts with closed volumes cannot be created due to the liquid medium.</td></tr>
<tr><td>Used materials</td><td colspan="2">acrylate, acrylic, epoxy</td></tr>
<tr><td>Material extrusion

</td><td>• Thermoplastic filament is passed through a heated print head as the print head moves over certain areas of the build plate;
• Once the layer is complete, either the print head or the build plate moves according to the height of the layer;
• Repeat steps 1 and 2 for the height of the piece;
• Support material is removed.</td><td>Advantages
- can be optimized for high material properties;
- reduced equipment costs.
Disadvantages
- low resolution and poor surface finish require significant post-processing;
- high residual stresses.</td></tr>
<tr><td>Used materials</td><td colspan="2">Acrylonitrile Butadiene Styrene (ABS), PLA, Acrylics, Polycarbonate (PC), Polyetherimide (PEI), High Impact Polystyrene</td></tr>
</table>

2.1 Factors affecting the FDM process

Below, in Table 2, the factors that are responsible for the quality of parts produced in Material Extrusion Three-Dimensional Printing (ME3DP-FDM) in terms of design and control system, printing process; as they affect process quality, surface finish, mechanical properties and dimensional accuracy of parts and/or printed products. Highlighting these provides a good breakdown of key factors and issues to consider during experimental review and future experimental design processes. They cover all the main aspects of computer design, machine design and materials design; used in most manufacturing processes to define the part or product.

Table 2. Important resource drivers and key aspects of the ME3DP process, [10]

Factor	Aspects	What affects
CAM: Design and Information System (as Control System)	- route planning; - part orientation;	- finishing the surface of the part; - mechanical properties of the part;
Equipment (FDM or FFF)	- 3D distribution speed or filament supply; - pressure and temperature gradient; - nozzle design;	- dimensional accuracy of the part; - Efficiency and effectiveness of processes;
Materials	- mold swelling; - long chain branching; - melt viscosity; - the crystallization speed of the molten material; - shear thinning induced by fitted molar mass distributions; - addition of stabilizers and other additives.	

The printing process depends on the printing framework, i.e. filament material, printing conditions, printing strategy and part geometry.

In order to target and evaluate the influence of the interface on material 3D printing, it was first necessary to establish some ground rules, namely:

- most printing parameters are the same for all materials (ie layer thickness, degree of fill, raster orientation, surface temperature, number of shells, etc.
- the parameters that can be adjusted for each material are the extrusion temperature, the temperature of the printing surface and the printing speed, [11].

3. MATERIALS AND METHODS

The materials selected to be analyzed in this study are part of the group of PLA biodegradable polymeric materials: PL, PLA HD Green and PL Impact Gray. These were produced by the Fiberology company and are based on renewable constituents such as corn starch, sugar beet pulp, sugarcans, cassava, tapioca roots etc.

The printing of the initially sample used for tribological tests was performed on the equipment Raise3d Pro2Plus and the printing the of worm wheel on a smaller printer - Tiertime UP 2 mini.

Obtaining the part (worm wheels) from the 3 raw materials (1.75mm - diameter) was done by 3D printing – FDM method, with a 100% filling degree, 50°C - heated bed, 0.4mm - nozzle diameter, 0.15mm - deposited layer thickness.

Calorimetric tests were performed on samples whose mass did not deposit 50mg for each material. The test interval was between (-253.15 --73.15) K with a 10k/min heating rate, in argon protection atmosphere.

The wear and friction coefficient tests were performed using the T-11 High-Temperature T -1-On-Disk testing equipment. The test conditions were: ball, circular movement on the sample surface -(20x20) mm, dry slip, 49N applied force, 40rpm angular speed, 5mm wear trace, 900s test time.

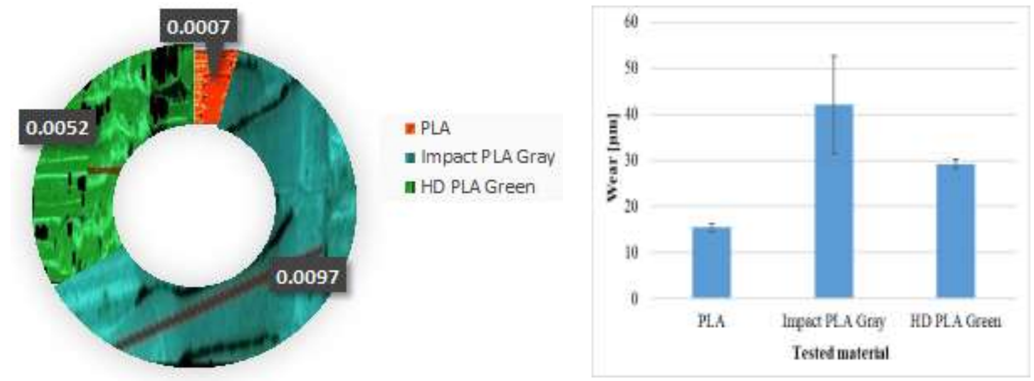
For the worm-worm wheel assembly the operation was simulated on a car wiper mechanism. During the simulation, the Romania climatic conditions have been set, temperatures, number of days per year. The test conditions were the following: 30°C (maximum annual temperature) - 4 working days, -10 ° C (minimum annual temperature) ≈ 4.34 working days and 18°C (average annual temperature) ≈10 working hours, [12-15].

The material from which they are made in the kod usual melcate wheels is the nylon.

The operation was simulated in the Discovery ATC DM600 Thermostat Climate Chamber.

4. RESULTS AND DISCUSSION

Based on preliminary tests regarding the functional characteristics of biodegradable polymers in the PLA class, their triobological tests (worm wheel parts) were performed during their operation on a movement simulation system made by car wipers.
Specifically, three types of polylaactic acid, PLA, HD PLA Green and Impact PLA Gray were selected, commonly used as alternatives for the petrochemical plastic at various applications.
The simulation of operating the worm wheel has been realized according to the operating conditions of some real wipers meaning, the environmental conditions in our country – Romania: precipitation, humidity, temperatures (minimum, medium and maximum) on The Discovery ATC DM600 Thermostatic Climate Chamber, [16].
As a result of the simulation, the behavior of their wear was observed, of course, being influenced by the properties of the printed benchmarks. According to the tribological studies carried out previously, the fact that the lowest friction coefficient was recorded by the PLA material-0.0007 were observed and the other two highlighted values closer, HD PLA Green-0.0052 and Impact PLA Gray-0.0097, Figure 1(a). Regarding the wear resistance of the tested samples before operation, it was observed that as expected their values are closely related to the values of the friction coefficient. Thus, the lowest value being also recorded by the PLA material and the highest by Impact PLA Gray, Figure 1(b), [16].



(a) (b)

Fig. 1. Results of PLA group of materials tribological testing:
(a) friction coefficient, (b) wear resistance

During operation in the thermal chamber that simulates the environmental conditions imposed during the study (presented in the previous chapter) it was observed that with the increase of the operating time and implicitly the operating temperature the samples behave different from the initial test - Pin -On-disk. Specifically, PLA was most affected during the simulation because it has the lowest melting point (158°C) compared to the other two materials (about 184°C), [17]. This aspect can be observed in Figure 2, which reflects the traces of wear on each worm wheel during the simulation, for the operating temperature of -10˚C.

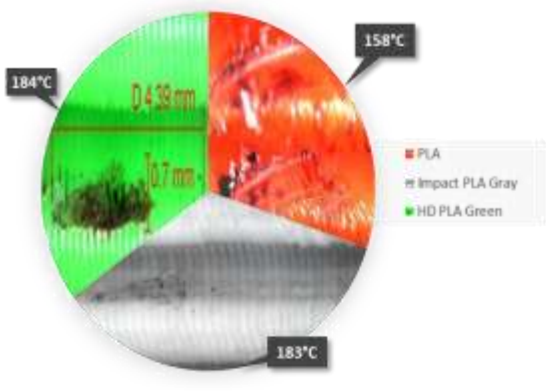


Fig.2. The thermal effect of wear on the printed worm wheels

5. CONCLUSIONS

According to the results obtained in the present study, the polymer that recorded the lowest values of the friction coefficient and wear (15.5 ± 0.8) is PLA but during the operation simulation his polymer has highlighted the smallest resistant to wear. But, even so the worm wheel tested within the mechanism is only suitable at negative operating temperatures of -10°C, not at high temperatures of 18°C or 30°C.
The increase in the friction coefficient for the HD PLA Green material resulted in small areas of thermally influenced material that did not interfere with the mechanism's operation. The operation is within normal parameters for -10°C negative temperatures. The highest coefficient of friction was measured for the Impact PLA Gray material, which obviously had the most wear.
The highest friction coefficient 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 same as the other biodegradable material, 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.

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