

Research into the tribological properties of fiber deposition strategies for 3D printed polycarbonate with FDM technology

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ABSTRACT

This paper deals with a detailed investigation of the tribological properties of polycarbonate (PC), which was manufactured using additive manufacturing technology, namely Fused Deposition Modeling (FDM). The main focus of the research is to analyze the impact of different layering strategies on the abrasive wear of the material, while maintaining consistent manufacturing conditions and printing settings. The samples were printed in different layering configurations, all of which were oriented vertically with respect to the printing axis. The chosen approach allowed us to investigate how different layer trajectories and orientations affect the mechanical and tribological properties of the resulting product. The manufactured samples were then subjected to standardized tests to evaluate abrasive wear, and the testing was carried out according to the methodology defined in ASTM G65/16 - Standard Test Method for Measuring Abrasive Wear Using Sand and Rubber Wheel. The aim of the experiment was to compare the effectiveness of different layer deposition strategies in terms of their ability to resist abrasive wear under identical loading conditions. Such an approach allowed to identify optimal configurations for increasing the service life of parts made of polycarbonate through 3D printing, especially for applications where the material is exposed to high mechanical stress. The test results provided a comprehensive overview of the influence of the layer orientation and the overall structure of the samples on their resistance to abrasive wear. Based on the data obtained, it was possible to identify the most effective layer deposition strategies that contribute to increased mechanical resistance and extended service life of PC products printed using FDM technology. This study also contributes to a broader understanding of the relationship between additive manufacturing parameters and functional properties of the output product, which is crucial for optimizing 3D printing in industrial practice.

KEYWORDS: fused deposition modelling, tribological properties, Polycarbonate

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I. INTRODUCTION

Additive manufacturing, commonly known as 3D printing, has been developing dynamically in recent years and is becoming one of the most innovative and progressive technologies in the field of manufacturing. Its basic principle is the layering of material based on a digital model, which allows the creation of complex geometries that would be difficult to implement using conventional methods. At the same time, this technology supports a wide range of composite materials, including those with added reinforcements, such as carbon fibers or metal powders, which significantly expands the possibilities of adapting the properties of final parts to specific requirements. Thanks to its flexibility, speed and ability to minimize waste material, 3D printing is increasingly used not only in research and development, but also in serial production in various industrial sectors, such as the automotive, aerospace, medical and electrical industries. It is expected that additive manufacturing will play a key role in transforming the way products are designed, manufacturing processes are optimized and manufacturing operations are organized in the coming years. Its impact will also be increasingly visible in the transition to digitalized, flexible and sustainable production systems, which are essential for the competitiveness of modern businesses in the Industry 4.0 environment [1]. In Fused Deposition Modeling (FDM), the most commonly used materials are ABS (acrylonitrile-butadiene-styrene) and polylactic acid (PLA). In addition, other materials are available, such as polycarbonate (PC), polyetherimide (PEI), polyamide (PA), PC-ABS blends and coated terephthalate (PET) [2-4]. The range of composite materials with the addition of fibers, Kevlar, powdered metals, graphene, carbon nanostructures and ceramics is also rapidly expanding. One

of the main advantages of FDM technology is its relatively low cost compared to other 3D printing methods [5-8]. This affordability is a result of the price of the printers and the open availability of materials. FDM is also growing in popularity due to its accessibility to ordinary consumers. The technical literature often focuses on the mechanical properties of printed materials, especially in relation to printing parameters, process results and the type of reinforcing fillings [9]. In recent years, the use of 3D printed products has increased significantly, which is due to the growing demand for components with high strength, improved performance characteristics and reliability. These properties can be achieved precisely through 3D printing, which makes it an ideal manufacturing method. The advantages of 3D printing include the ability to produce homogeneous, lightweight and light parts, minimize waste material, while achieving high-precision shapes, production and costs due to automation. Moreover, this technology is necessary for being environmentally friendly [10]. Thanks to these advantages, 3D printing has found application in various industries, such as aviation, automotive and food industry [11-13]. There are several additive manufacturing methods, such as Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS), with FDM being the most widespread of them – due to its ease of production and availability. This study also focuses on this aspect. The mechanical properties of 3D printed parts produced by the FDM method are significantly influenced by the printing parameters. Nowadays, surface textures are increasingly being incorporated into the designs of parts, which serve to improve tribological properties. The aim of this study is therefore to analyze the influence of different printing parameters on the tribological performance of 3D printed samples with surface texture. Wear is a complex condition occurring on the surface of components and depends on the operating conditions, the mechanical particles acting on them, the equipment parameters and the properties of the contact surfaces [14]. The physical interactions between the abrasive parts and the worn surface are investigated in order to elucidate the deformation and wear mechanisms. These interactions can be divided into four types: micro-ploughing, micro-cutting, micro-fatigue and micro-cracking [15-16].

II. MATERIALS AND METHODS

Additive technology is also among the new and modern trends in the production of various models and prototypes. By additive manufacturing we can imagine the creation of a model in layers by sintering powders, molten plastic, etc... A huge advantage is that with this technology we can produce parts of different external and internal shapes, which brings us many advantages.

- Creating a complex model at once,
- reducing production time and saving costs,
- increasing reliability,
- avoiding rejects and defects.

Materials used for RP production:

- Photopolymers,
- thermoplastics,
- metal powders,
- special paper and many others.

Despite the great advances in additive manufacturing in recent years, there is still a gap between methods differing in speed, precision, material and cost. The difference is mainly between sophisticated printers and between domestic printers, an example of deposition of layers by FDM method is shown on Figure 1.

Polycarbonate test samples were printed on a printer. on a Fortus 400mc printer with a fiber width of 0.5 mm.

Fortus 400mc basic specifications are listed below:

- print area 406 x 355 x 406 mm,
- the minimum layer height is 0.127 mm,
- the maximum layer height is 0.330 mm

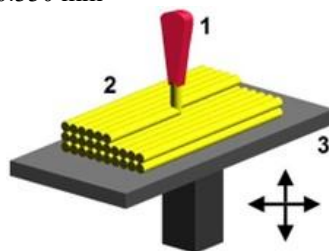


Figure 1 Example of FDM layering

The samples were printed in the vertical direction in height. filling strategy around the worn surface of the material Figure. 2. 5 strategies were selected Figure. 3. 3 samples were printed from each strategy and labeled as M $\cdot$,M $\cdot\cdot$,M $\cdot\cdot\cdot$.

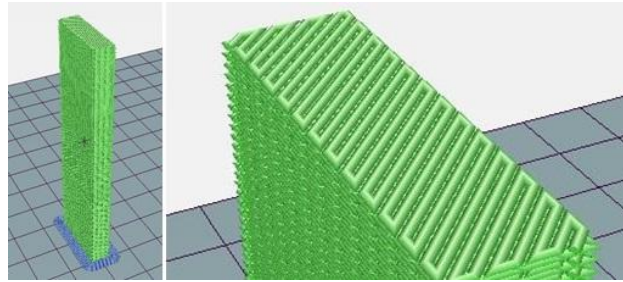


Figure 2 Demonstration of vertical fiber laying

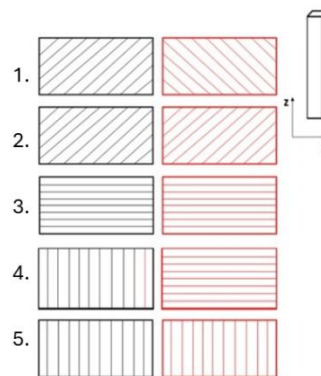


Figure 3 Press strategy 1-5

Testing of the samples was performed on ASTM G65 test equipment. Dry sand/rubber disc abrasion test Figure 4.. The essence of this test is to abrade a standard test specimen by controlling the grit size and composition of the abrasive material. In the test, abrasive is introduced between the test specimen and the rotating wheel. The wheel is covered with an achlorobutyl rubber surround around the perimeter which has a specified hardness. The specimen is pressed against the rotating wheel at a clearly specified force by means of a lever arm while a controlled flow of abrasive media is abraded over the surface of the test specimen. The rotation of the wheel is in the direction of the contact surface of the sand flow. The axis of rotation and the lever arm lie in a plane which is approximately tangential to the surface of the rubber wheel on which the load is applied. The test specimens shall be weighed before the experiment and the specimens shall be reweighed after the test. This test will establish the weight loss of material that has occurred. As mentioned in the explanation of abrasive wear so in this case it is a three-point wear which means that we have added free particles (abrasive) to the two friction materials as free moving in the form of gravity gradient. The parameters at which the experiment was conducted are recorded in Table 1.

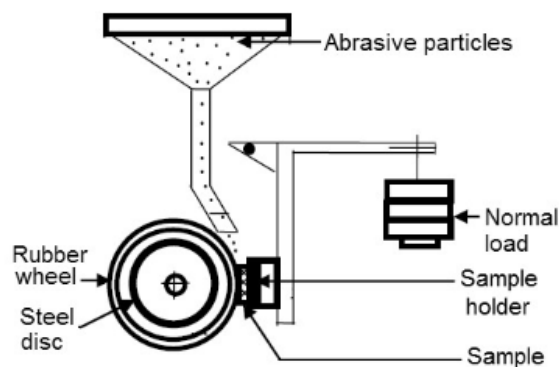


Figure 4 ASTM G65

When testing the samples, all data was stored and recorded in the PC using the sensors stored in the devices. The data they recorded were:

- Frictional force
- Load
- Temperature
- Number of revolutions
- Track length.

Table 1 Process parameters for the experiment

Sample size (mm)	70x20x6
Abrasive	Garnet $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
Speed (rpm)	200
Wheel diameter (mm)	229
Load (N)	25
Speed (m/s)	2,5
Distance (m)	278

III. MEASUREMENT RESULTS

After the experiment, all samples were cleaned with a BANDELIN ultrasonic cleaner for 30 minutes in methanol and then weighed to final weight. The balance used for the samples was a RADWAG XA220 with an accuracy of 1 mg.

These results show that the right choice of fiber deposition strategy can significantly influence the tribological properties of 3D printed materials and their suitability for various applications.

By changing the orientation of the construction of the samples, in which the samples were oriented vertically in the Z and X axes, there were changes in the abrasive wear of individual strategies. The first compared pair of strategies was combination No. 1 and No. 3 Figure 5. When these strategies were evaluated against each other, it was found that weight loss was very similar, with almost identical results. Weight loss ranged from 0.34% with strategy No. 3 up to 0.38% for strategy No. 1 Table 2 and Figure 6 .

Based on the data from the graph in Figure 6, we can conclude that strategy No. 3 shows better resistance to abrasive wear compared to strategy No. 1. This difference, although slight, indicates that the orientation and method of deposition of the layers (in this case, the vertical orientation of the samples in the Z and X axes) has a significant effect on the tribological properties of the material, namely its resistance to wear. Strategy No. 3 thus provides better performance in terms of abrasive wear, which makes it preferable to strategy No. 1 in the tested conditions

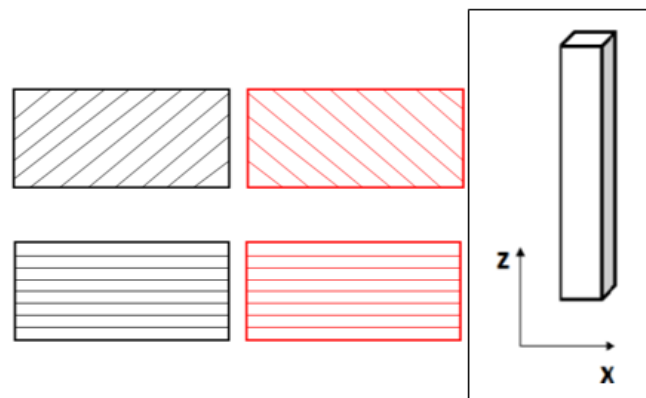


Figure 5 Used strategies No. 1 and No. 3

Table 2 Expression of weight and its loss in (g) and (%) for strategy No. 5 and No. 7

	strategy 1	strategy 3
Weight (g)	13.3356	13.0743
Weight loss (%)	0.3817	0.3355
Weight loss (g)	0.0508	0.0439

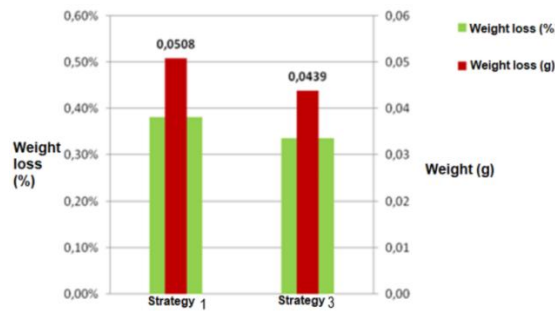


Figure 6 Graphic representation of weight loss in (g) and (%) for targets No. 1 and No. 3

Other strategies that were chosen for comparison were strategy No. 4 and No. 5 Figure7. Samples produced by these strategies have similar properties within the experiment. The weight loss percentages are almost the same Figure 8.

However, strategy No. 4 proved to be less advantageous compared to strategy No. 5 Table3. In strategy No. 4, the last layer of the layer was oriented in the direction of the applied forces of the test disc, which should theoretically improve the wear resistance. Nevertheless, the sample obtained by this strategy proved to be more susceptible to weight loss compared to the sample produced by strategy No. 5.

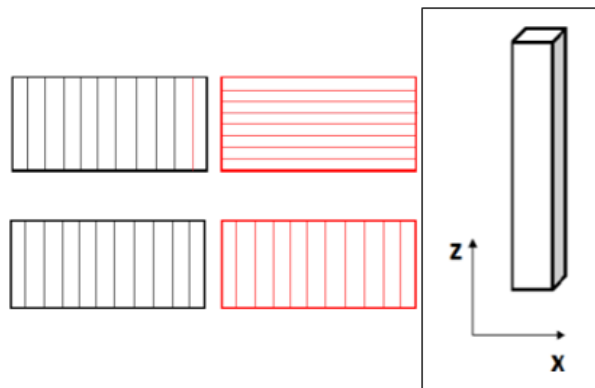


Figure 7Used strategies No. 4 and No. 5

Table 3Expression of weight and its loss in (g) and (%) for strategy No. 4 and No. 5

	strategy 4	strategy 5
Weight (g)	13.141	13.1379
Weight loss (%)	0.3273	0.3603
Weight loss (g)	0.0431	0.0473

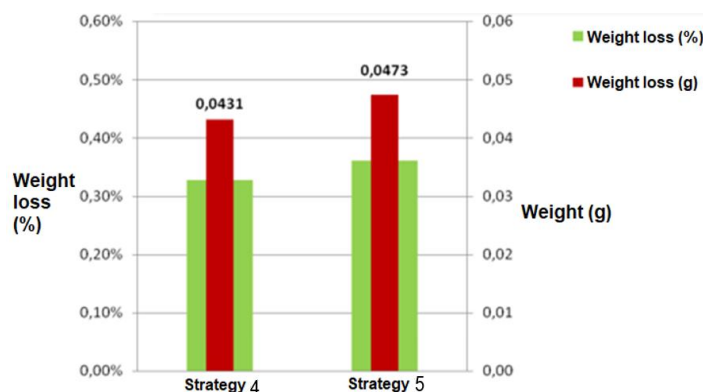


Figure 8Graphic representation of weight loss in (g) and (%) for targets No. 4 and No. 5

or further comparison, strategies No. 3 and No. 5. In strategy No. 3, the fibers were applied in the Z-axis direction, which replicates the direction of the applied forces in the abrasion test see Figure9. In this strategy, the layers were not combined, but each layer was applied in the same direction. In contrast to strategy No. 9, which differs by rotating the layers by 90°.

The results showed that the weight loss is lowest in the sample produced by strategy No. 5, which showed a weight layer of 0.15% see Table 4 and Figure 10. It follows that the orientation of the fibers in the Z-axis direction, ensured by parallel forces during the test, provides better resistance to abrasive wear compared to strategy No. 9, where the arrangement of the layers was different.

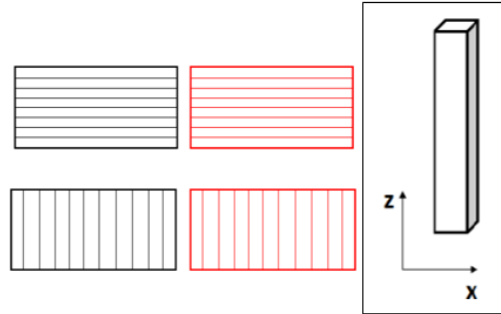


Figure 9 Used strategies No. 3 and No. 5

Table 4 Expression of weight and its loss in (g) and (%) for strategy No. 3 and No. 5

	strategy 3	strategy 5
Weight (g)	13.3504	13.1379
Weight loss (%)	0.1536	0.3603
Weight loss (g)	0.0439	0.0473

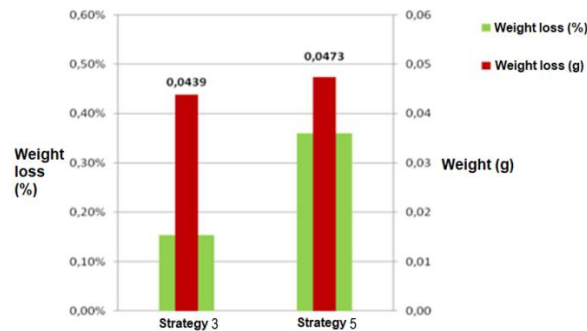


Figure 10 Graphic representation of weight loss in (g) and (%) for targets No. 3 and No. 5

The last strategies tested were strategy No. 1 and 2 Figure 11. There were no significant differences in weight loss in the abrasion test, which is related to the similar fiber orientation in both of these strategies. In both cases, the fibers are oriented at 45°, resulting in very similar tribological properties and hence minimal differences in weight loss Figure 12, Table 5.

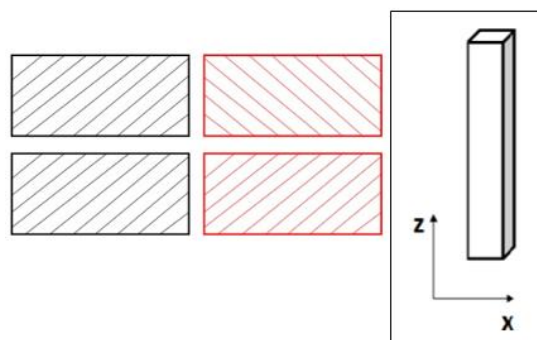


Figure 11 Used strategies No. 1 and No. 2

Table 5 Expression of weight and weight loss in (g) and (%) for strategies 1 and 2

	Strategy 1	strategy 2
Weight (g)	13.3356	13.4142
Weight loss (%)	0.3817	0.4778
Weight loss (g)	0.0508	0.0641

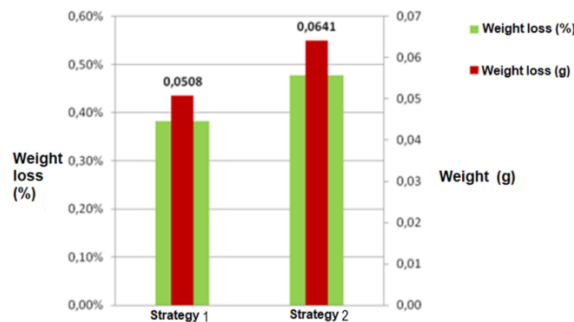


Figure 12 Graphic representation of weight loss in (g) and (%) for targets No. 1 and No. 2

IV. RESULTS AND DISCUSSION

From the graph Figure 13 it is possible to observe only a minimal difference in the weight of individual samples, which concerns approximately the same material consumption for most of the printing strategies used. The most significant impact on the weight consists of priorities 1 and 2, in which the filament is deposited at an angle of 45°. These strategies were implemented in a vertical orientation of the layers. It is assumed that this configuration leads to a higher material density and at the same time to a larger volume of filament consumed (in mm³), which directly contributes to an increase in the total weight of the samples. On the contrary, the largest pieces in weight were recorded for strategies 3, 4 and 5, where the filament was deposited at a right angle (90°) either in the direction of the X-axis or the Y-axis. These orientations probably lead to a less efficient filling of the internal spaces, which can cause the density and therefore the decisive weight of the resulting parts. These findings indicate that the method of filament deposition has a direct impact not only on the mechanical but also on the tribological properties of the printed components. Based on the results obtained so far, it can be concluded that the most suitable strategy for ensuring higher wear resistance as well as better tribological properties is the printing strategy of filament at an angle of 45°. This orientation probably contributes to better cohesion between individual layers and reduces the risk of delamination during mechanical loading. The results support the hypothesis that optimization of the printing angle is of fundamental importance for improving the functional properties of 3D printed components.

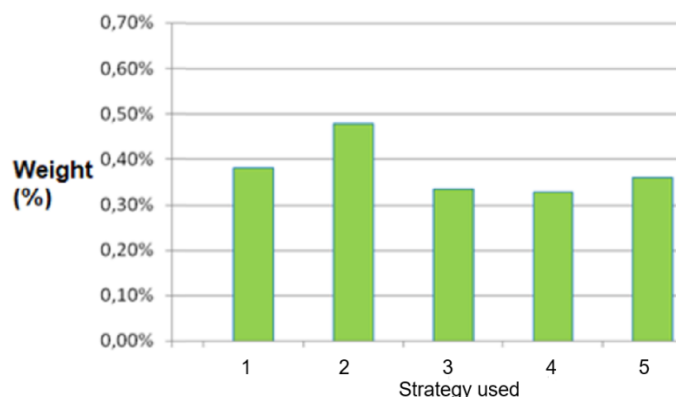


Figure 13 Average percentage of weight loss

V. CONCLUSION

One of the key technologies of additive manufacturing is fused deposition modeling (FDM), which is one of the most widespread and accessible methods of 3D printing. With the increasing number of its practical applications in industry, research and development, the need for detailed investigation of the properties of materials processed by this technology is also growing. Particular emphasis is placed on the mechanical properties of these materials, as well as their resistance to surface wear, friction and other forms of degradation

that arise under real load on components. Current research is therefore intensively focused on the analysis of the most commonly used thermoplastic polymers in the context of tribological tests and mechanical load. These materials include polycarbonate (PC), which is one of the high-performance plastics with a wide range of applications. Its popularity lies mainly in its exceptional properties – high impact strength, excellent mechanical strength, good dimensional stability and heat resistance. These parameters make PC suitable for demanding applications, including the production of functional parts using 3D printing. In the field of experimental evaluation of tribological properties, a pin-on-disc device (in this case FCCCD – Friction and Circular Contact Characterization Device) is often used, which allows for accurate simulation of wear under controlled conditions. During testing, various variables are monitored, such as normal load (force acting perpendicular to the contact surface), sliding speed (relative speed of movement between the sample and the abrasive disc) and the orientation of the layers within the printed sample, which significantly affects the internal structure and resistance of the material to damage. These research activities are extremely important in terms of increasing the level of knowledge about the behavior of polymers under tribological stress, which subsequently allows for their more effective and targeted use in technical applications. Knowledge of these properties is crucial for the design of parts that must withstand mechanical friction and abrasive environments, such as moving parts, bearing surfaces, gearing or housings of technical equipment. In this research, polycarbonate (PC) was chosen as a model material, and the aim was to experimentally verify its resistance to abrasive wear under different layer deposition strategies during the FDM process. The study focused on evaluating tribological properties – in particular the coefficient of friction and wear rate – and also analyzed the influence of the layer design on the structure of the surface and subsurface areas of the samples. Experimental measurements were performed according to the ASTM G65-16 standard, which defines procedures for evaluating abrasive wear using dry sand in a pin-on-disc system. 15 samples were prepared for testing, divided into five groups according to different layer deposition strategies. Each strategy was represented by three identical samples to ensure repeatability and reliability of the results. The key parameter evaluated was the weight loss of the samples as a function of the distance the sample traveled during the abrasion test. The results clearly show that the way the filament is oriented – i.e. the direction in which the layers are deposited during 3D printing – has a fundamental impact on the wear resistance of the samples. The differences in weight loss found between the individual strategies confirm that the internal microstructure of the material created by the FDM process significantly affects the overall tribological behavior of the print. This knowledge can serve as a basis for optimizing printing parameters in order to increase the functionality and durability of 3D printed parts, and at the same time shows the importance of choosing the right printing strategy when manufacturing parts that are exposed to mechanical wear.

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