RESEARCH OF THE RESISTANCE OF POLYCARBONATE SAMPLES MADE BY FDM TECHNOLOGY TO ABRASIVE ACTION

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DOI: 10.17973/MMSJ.2024_12_2024107

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The article deals with the investigation of tribological properties of polycarbonate (PC) material produced by 3D printing using Fused Deposition Modelling (FDM) technology under different layer deposition strategies and their subsequent testing for abrasive wear. The aim of the experiment was to compare the effect of different layer deposition strategies in the FDM process on the abrasive wear of the material at specified process parameters, which were defined according to ASTM G65 standardized tests. Based on these tests, the different strategies were compared and evaluated in terms of their ability to resist abrasive wear, providing insight into the effect of different orientations and layer arrangements on the tribological properties of 3D printed polycarbonate.

KEYWORDS

3D printing, fused deposition modelling, tribological properties, Polycarbonate

1 INTRODUCTION

Additive Manufacturing (AM), or 3D printing, is rapidly emerging as one of the most innovative and promising technologies for producing structural components. It supports the use of various composite materials, opening up new opportunities in manufacturing. As a result, 3D printing is anticipated to be a crucial technology in shaping the future of product design, manufacturing processes, and factory operations [Fornea 2015]. The most commonly used materials in Fused Deposition Modeling (FDM) technology include ABS plastic (acrylonitrile butadiene styrene) and polylactic acid (PLA). Other materials, such as polycarbonate (PC), polyetherimide (PEI), polyamide (PA), PC-ABS (a blend of polycarbonate and ABS), and polyethylene terephthalate (PET), are also available [Campbell 2013]. Additionally, there is a growing range of composite materials incorporating additives like carbon fibre (CF), Kevlar, powdered metals, graphene, carbon nanostructures, and ceramics. One of the key advantages of FDM technology is its relatively low cost compared to other 3D printing methods [Carneiro 2015]. This is due to both the affordable price of FDM printers and the wide availability of materials. The technology has also gained popularity due to its accessibility at consumer-friendly prices. Research in the literature often focuses on the mechanical properties of printed materials, particularly in relation to printing parameters, process outcomes, and the types of reinforcing fillers used [Tekinalp 2014].

In recent years, the use of three-dimensional (3D) printed products has grown significantly, driven by the increasing demand for high-strength components that offer improved performance and reliability [Anisimov 2019]. These characteristics can be achieved through 3D printing, making it an ideal manufacturing technique. The key advantages of 3D printing include the ability to produce homogeneous, strong, and lightweight parts, minimize material waste, create complex shapes with high accuracy, enable fast production, and reduce costs due to automated processes. Additionally, 3D printing is considered environmentally friendly [Sukhodub 2018, Tofail 2018, Shahrubudin 2019, Jimenez 2019]. These benefits have led to the widespread adoption of 3D printing in various industries, including aerospace, automotive, and food production [Ventola 2014, Dodziuk 2016]. There are several methods available for producing 3D printed parts, such as Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS). Among these, FDM is the most commonly used method due to its ease of fabrication, and it is the focus of the present study.

The mechanical properties of 3D printed components produced using FDM are heavily influenced by the printing parameters. Furthermore, to enhance the tribological performance of 3D printed parts, surface textures are often incorporated in recent designs. As a result, this study aims to analyze how various printing parameters affect the tribological performance of 3D printed samples with textured surfaces.

The wear mechanism is a complex process occurring on the surface of the parts, which is dependent on the operating conditions in which the mechanical particles are applied and on the parameters of the machines and on the properties of the contact surfaces [Suchanek 2009].

The physical interactions between the abrasive particles and the abraded surface are studied in order to clarify the mechanisms of deformation and wear and can be divided into four types: microploughing, microcutting, microfatigue and macrocracking [Zum Gahr 1987].

2 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 Fig. 1.

Polycarbonate test samples were printed on a printer. on a Fortus 400mc printer with a fibre 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.

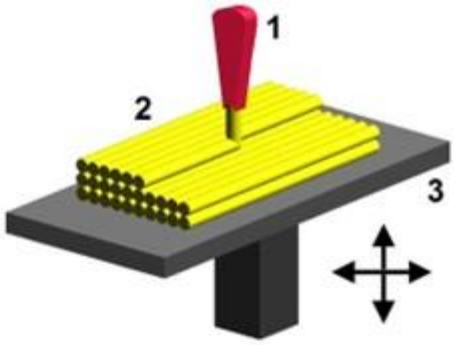

Figure 1. Example of FDM layering

For samples 1-4, the filled strategy is applied parallel to the surface tested for wear Fig. 2 and in the second case for samples 5-9, the filling is applied perpendicular to the wear surface of the material Fig. 3. 9 strategies Fig. 4 and three samples from each strategy were marked as M·, M··, M···.

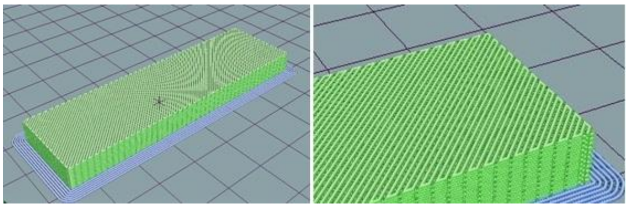

Figure 2. Press strategy 1-4

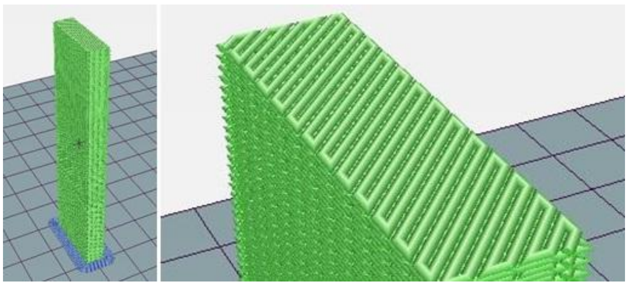

Figure 3. Press strategy 5-9

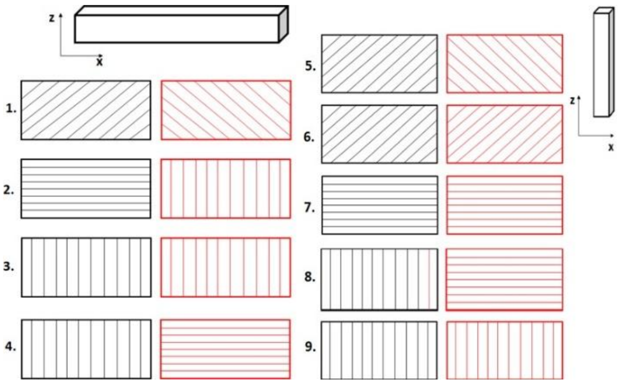

Figure 4. Fibre deposition strategies used for both sample types

2.1 *Testing samples for abrasive wear according to ASTM G65*

Testing of the samples was performed on ASTM G65 test equipment. Dry sand/rubber disc abrasion test Fig. 5. 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.

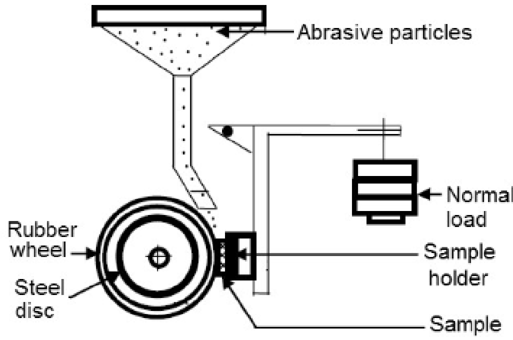

Figure 5. ASTM G65

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 $Fe_3Al_2(SiO_4)_3$
Speed (rpm)	200
Wheel diameter (mm)	229
Load (N)	25
Speed (m/s)	2,5
Distance (m)	278

3 MEASUREMENT RESULTS

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

The first compared pair of strategies were strategy No. 1 and No. 2. During the evaluation of these two strategies, strategy No. 2 as a more suitable variant compared to strategy No. 1. This difference can be explained by the way fibres are used in the layers, which in strategy No. 2 copy the axis of the wheel and are parallel to the application of the force during the test. the arrangement of the fibres provides resistance to abrasive wear, as the fibres are oriented in the direction during testing.

On the contrary, in strategy No. 1, the fibres in the sample are oriented alternately at an angle of 45° in each layer, with each new layer applied in the opposite direction to the previous one. When evaluating the weight loss of the samples, it was shown that sample No. 2 there was a weight loss of 0.054% (see Fig. 7), which is approximately half the weight loss compared to sample No. 1, which showed greater weight loss (Tab. 2 and Fig. 6). This result confirms that strategy No. 2, with fibres oriented in the direction of the applied force, is more effective from the point of view of abrasive wear than strategy No. 1.

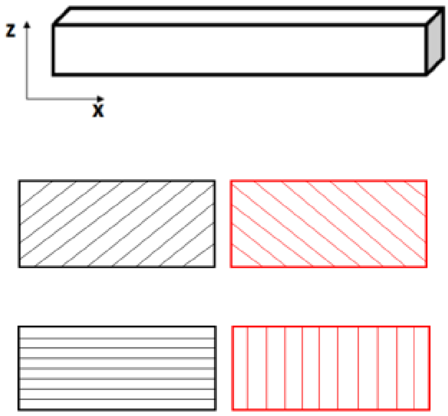

Figure 6. Used strategies No. 1 and No. 2

Table 2. Expression of weight and its loss in (g) and (%) for strategy No. 1 and No. 2

	strategy 1	strategy 2
Weight (g)	13.4785	13.1423
Weight loss (%)	0.2111	0.4068
Weight loss (g)	0.0285	0.0535

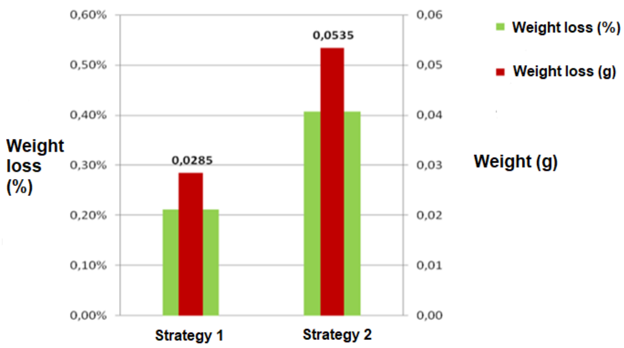

Figure 7. Graphic representation of weight loss in (g) and (%) for targets No. 1 and No. 2

In the next step of comparing the material's resistance to abrasive wear, strategy No. 2 and No. 4 (Fig. 8). When examining these two strategies, strategy No. 4, which shows better wear resistance compared to strategy No. 2. This difference is caused by the orientation of the fibres in the last layer, which was in strategy No. 4 acting in the direction of the force of the friction wheel during the test.

Such an arrangement of the fibres in the direction of the applied force allowed the sample produced by this strategy to resist wear more effectively, which was reflected in a lower weight loss. For the sample produced by strategy No. 4 there was a percentage weight loss of only 0.0205%, while the sample produced by strategy No. 2 showed a greater decrease (Tab. 3 and Fig. 9). This result confirms that the orientation of the fibres in the direction of the applied force plays a key role in improving the material's resistance to abrasive wear.

A similar phenomenon was also observed when comparing samples produced by strategy No. 3 and strategy No. 4 (see Figure 9), while again the orientation of the fibres in the samples played a decisive role. In strategy No. 4, the last layer of fibres was applied in the direction of the axis of the applied forces of the friction disc, which allowed a better distribution of forces during the test and improved the resistance of the sample to abrasive wear. This fibre orientation, which was parallel to the application of the force during the test, leads to a more efficient distribution of the load, which slows down the wear process.

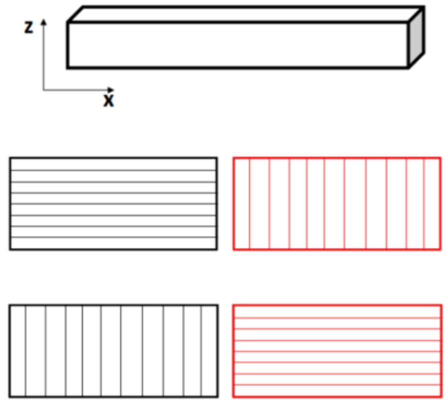

Figure 8. Used strategies No. 2 and No. 4

Table 3. Expression of weight and its loss in (g) and (%) for strategy No. 2 and No. 4

	strategy 2	strategy 4
Weight (g)	13.1423	13.3504
Weight loss (%)	0.4068	0.1536
Weight loss (g)	0.0535	0.0205

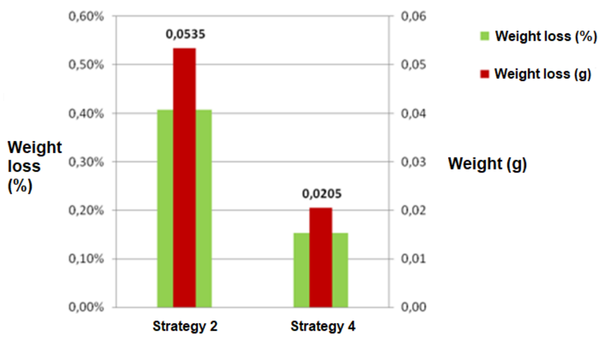

Figure 9. Graphic representation of weight loss in (g) and (%) for targets No. 2 and No. 4

On the other hand, samples produced by strategy No. 3 showed the greatest weight loss – up to 0.4105% (Tab. 4 and Fig. 11), which is a significantly higher loss compared to strategy No. 4. This greater weight loss indicates that the fibre orientation in strategy No. 3 perpendicular to the axis of the forces acting during the test are not a suitable choice from the point of view of more pronounced wear. These results show that the orientation of the fibres in the direction of the applied force, as in the case of strategy No. 4, has a significant effect on the tribological properties of the material, specifically its resistance to abrasive wear. Strategy No. 4, which allows fibres to be oriented to follow the direction of applied forces, provides significantly better wear protection than strategy No. 3 where the fibres are not in the ideal direction with respect to the application of the force. This difference in durability is especially important in applications where long-term durability and wear resistance must be guaranteed.

As part of the last comparison of fibre deposition strategies in the directions of the X and Z axes, strategies No. 3 and No. 4 (see Figure 10). Both strategies show similar results in terms of abrasive wear, which is similar to the findings when comparing strategies No. 1 and No. 2. However, in a more detailed evaluation of weight loss, strategy No. 4 showed better results than strategy No. 1, indicating a lower degree of attrition when using this strategy. This difference in weight loss is clearly visible in Table 5 and Figure 13, where a lower weight loss can be observed for samples printed using strategy No. 4 compared to strategy No. 1.

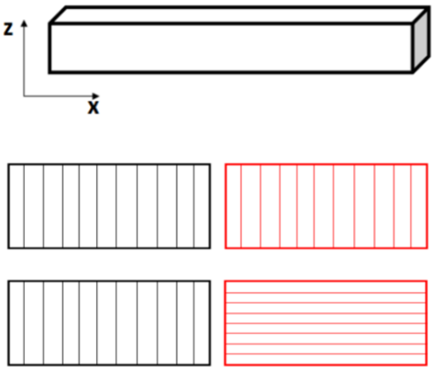

Figure 10. Used strategies No. 3 and No. 4

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

	strategy 3	strategy 4
Weight (g)	13.4507	13.3504
Weight loss (%)	0.4105	0.1536
Weight loss (g)	0.0552	0.0205

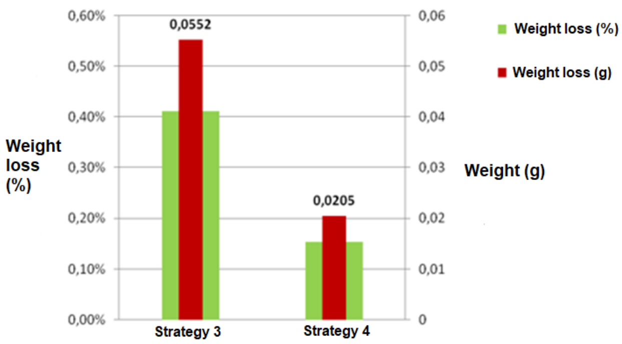

Figure 11. Graphic representation of weight loss in (g) and (%) for targets No. 3 and No. 4

From the perspective of abrasive wear, these strategies offer very similar results, indicating that the orientation of the fibres in the direction of the X and Z axes has a significant effect on the resistance of the material to this type of wear. However, thanks to lower weight loss and better results in wear tests, strategy No. 4 appears to be more advantageous compared to strategy No. 1. In conclusion, we can conclude that strategy No. 4 and No. 1 best in terms of their abrasion resistance, while strategy No. 4 shows better overall abrasion resistance, especially in terms of weight loss and wear resistance.

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

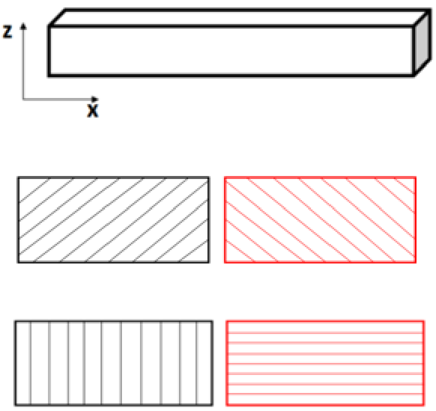

Figure 12. Used strategies No. 1 and No. 4

Table 5. Expression of weight and its loss in (g) and (%) for strategy No. 1 and No. 4

	strategy 1	strategy 4
Weight (g)	13.4785	13.3504
Weight loss (%)	0.2111	0.1536
Weight loss (g)	0.0285	0.0205

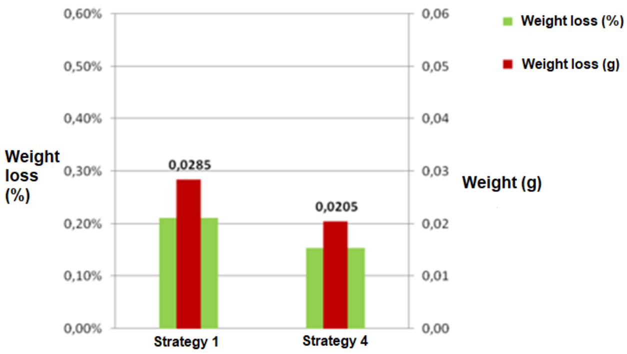

Figure 13. Graphic representation of weight loss in (g) and (%) for targets No. 1 and No. 4

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. 5 and No. 7 (Fig. 14). 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. 7 up to 0.38% for strategy No. 5 (Tab. 6 and Fig. 15).

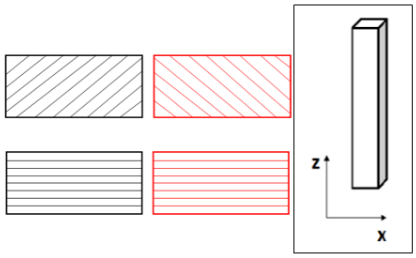

Figure 14. Used strategies No. 5 and No. 7

Table 6. Expression of weight and its loss in (g) and (%) for strategy No. 5 and No. 7

	strategy 5	strategy 7
Weight (g)	13.3356	13.0743
Weight loss (%)	0.3817	0.3355
Weight loss (g)	0.0508	0.0439

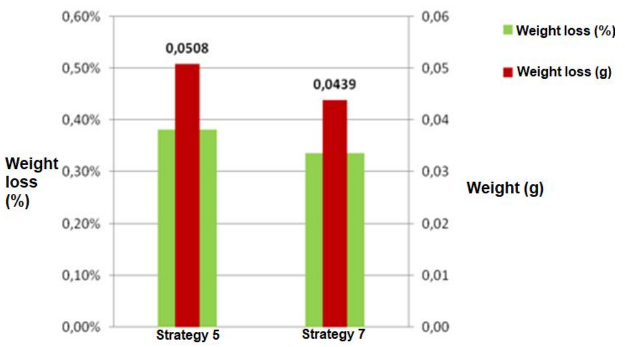

Figure 15. Graphic representation of weight loss in (g) and (%) for targets No. 5 and No. 7

Based on the data from the graph in Fig. 15, we can conclude that strategy No. 7 shows better resistance to abrasive wear compared to strategy No. 5. 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. 7 thus provides better performance in terms of abrasive wear, which makes it preferable to strategy No. 5 in the tested conditions.

Other strategies that were chosen for comparison were strategy No. 8 and No. 9 (Fig. 18). Samples produced by these strategies have similar properties within the experiment. The weight loss percentages are almost the same.

However, strategy No. 8 proved to be less advantageous compared to strategy No. 9 (Tab. 7). In strategy No. 8, 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. 9.

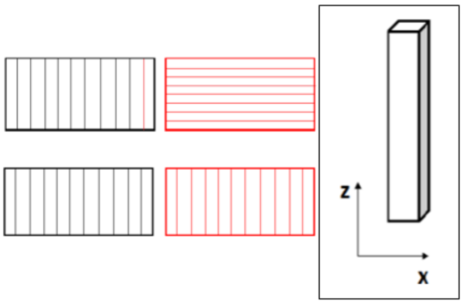

Figure 16. Used strategies No. 8 and No. 9

Table 7. Expression of weight and its loss in (g) and (%) for strategy No. 8 and No. 9

	strategy 8	strategy 9
Weight (g)	13.141	13.1379
Weight loss (%)	0.3273	0.3603
Weight loss (g)	0.0431	0.0473

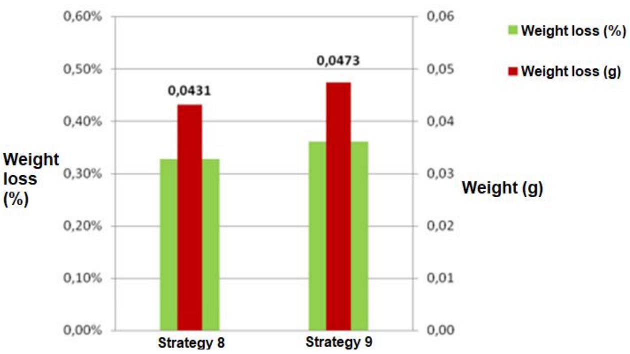

Figure 17. Graphic representation of weight loss in (g) and (%) for targets No. 8 and No. 9

For further comparison, strategies No. 7 and No. 9. In strategy No. 7, the fibres were deposited in the direction of the Z axis, which copies the direction of the applied forces in the abrasive test (see Fig. 16). 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 turning the layers by 90°.

The results showed that the weight loss is the lowest in the sample produced by strategy No. 7, which showed a weight layer of 0.15% (see Tab. 8 and Fig. 19). This result, that the orientation of the fibres in the direction of the Z axes, provided by parallel forces during the test, provides better resistance to abrasive wear compared to strategy No. 9, where there was a different arrangement of the layers.

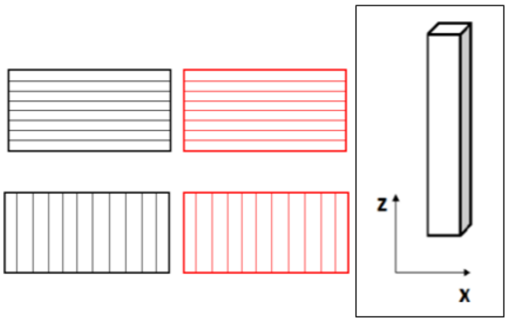

Figure 18. Used strategies No. 7 and No. 9

Table 8. Expression of weight and its loss in (g) and (%) for strategy No. 7 and No. 9

	strategy 7	strategy 9
Weight (g)	13.3504	13.1379
Weight loss (%)	0.1536	0.3603
Weight loss (g)	0.0439	0.0473

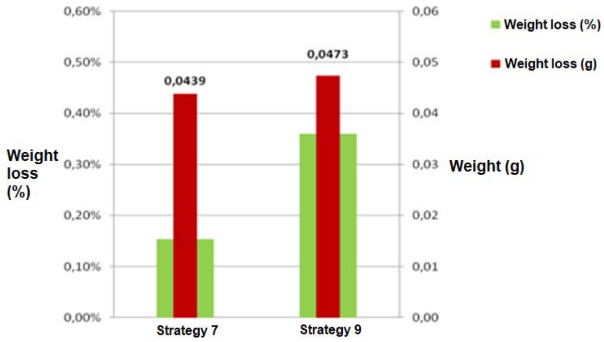

Figure 19. Graphic representation of weight loss in (g) and (%) for targets No. 7 and No. 9

The last strategies tested were strategy No. 5 and 6 (Fig. 19). There were no significant differences in weight loss in the abrasion test, which is related to the similar fibre orientation in both of these strategies. In both cases, the fibres are oriented at 45°, resulting in very similar tribological properties and hence minimal differences in weight loss (Fig. 21, Tab. 9).

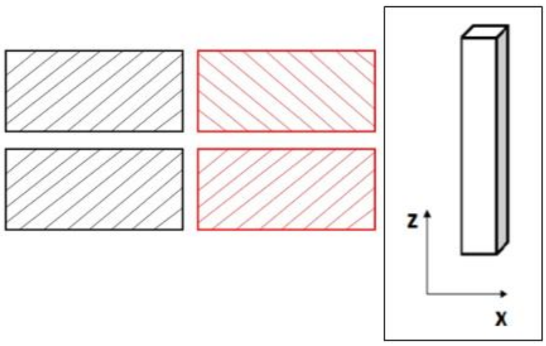

Figure 20. Graphical representation of weight loss in (g) and (%) for strategies 5 and 6

Table 9. Expression of weight and weight loss in (g) and (%) for strategies 5 and 6

	strategy 5	strategy 6
Weight (g)	13.3356	13.4142
Weight loss (%)	0.3817	0.4778
Weight loss (g)	0.0508	0.0641

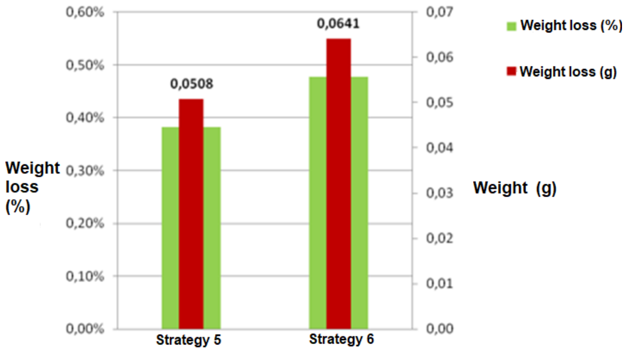

Figure 21. Graphical representation of weight loss in (g) and (%) for strategies 5 and 6

From the graph (Fig 22, Fig. 23) we can see the minimal differences in the weights where between the lowest and the highest weight is 0.4498 g. The greatest effect of strategy on the weight of the samples is strategy 1, 5 where the filaments are deposited at an angle of 45°, strategy 5 was synthesized vertically and strategy 1 horizontally for these strategies is also assumed the greatest sample density with the largest volume of filament used in mm^3. Strategies #2, #3 experienced an underweight loss pattern in the abrasion test the filaments were oriented horizontally and their filaments were not at a 45° inclination. For strategies No. 7, No. 8 and No. 9, the filaments were deposited vertically on the 3D printer substrate, while strategy No.9 did not combine the filament deposition in the sample, and from the loss point of view, strategy No. 9 was the most advantageous of these types at Fig. 22 and Fig.23.

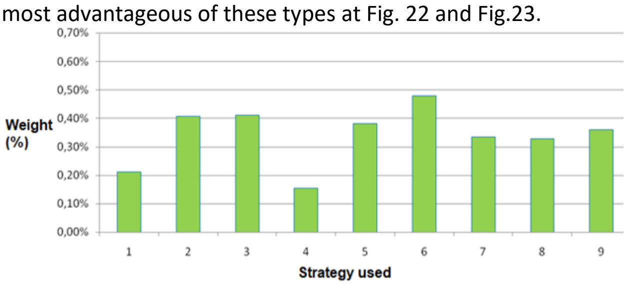

Figure 22. Average percentage of weight loss

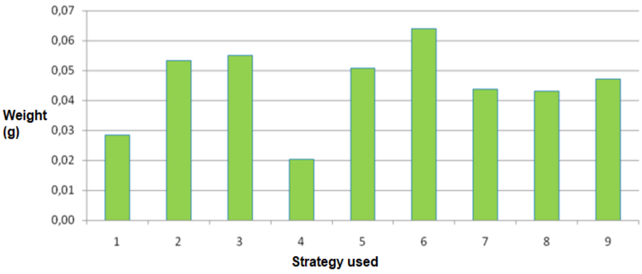

Figure 23. Average weight loss in grams

4 CONCLUSION

3D printing is now increasingly used in various industrial fields. One of these technologies is the fused filament-based manufacturing (FDM) process. With the increasing number of applications and demand for this technology, it is necessary to further investigate the mechanical properties of materials as well as their resistance to surface wear and various forms of wear.

Current research will focus primarily on the most commonly used materials in the field of experimental investigation of friction and impact, with polycarbonate (PC) being one of the most commonly investigated polymers. This material is popular for its high mechanical strength, impact resistance, and good thermal stability, making it suitable for a wide range of applications, including those made using 3D printing.

In research focusing on samples made from Fused Deposition Modelling (FDM), experiments are often transferred to pin-on-disc (FCCCD) devices, which allows real wear conditions to be simulated. During these experiments, various factors that can influence the results are taken into account, such as normal load (applied perpendicular to the surface), slip velocity (the rate of movement between two surfaces) and specimen orientation, which refers to the way the layers of material are oriented in 3D printing.

This type of research is crucial for a better understanding of the mechanical properties of materials used in 3D printing, which is essential for their effective application in both industrial and commercial sectors.

The selected material, polycarbonate (PC), enables the use of 3D printed products in more demanding applications and was therefore subjected to experimental measurements of its resistance to abrasive wear. This study focuses on the analysis of the influence of the Fused Deposition Modelling (FDM) technique on the tribological properties of polycarbonate, namely on the behaviour of the friction coefficient and the wear behavior of the samples, as well as on the properties of the surface and subsurface layers.

In the experiment, the weight loss of the specimens was measured according to ASTM G65-16, and the effect of different deposition strategies of the layers was evaluated. A total of 18 specimens prepared by 9 different layer deposition strategies were used, with each strategy represented by three specimens. The main factors investigated in the experiment were weight loss versus distance travelled. The results show that filament orientation and layer deposition method in 3D printing have a significant effect on the tribological properties of the material. Different filament orientations caused differences in weight loss which affected the overall wear resistance of the material.

ACKNOWLEDGMENTS

This research was funded by the grant KEGA 018TUKE-4/24.

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