

Determining the tribological properties of different 3D printing filaments

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Abstract. The paper aims to determine the friction coefficient and wear behaviour of different 3D filaments in contact with a metallic disc. The method used for testing was the pin-on-disc method, where 3D half inch diameter pins with a half sphere end were printed out of the different filaments and rotated on the disc. The optimal time for measuring the friction coefficient was determined by observing when a sudden change in friction was recorded by the sensor as a result of material deposition on the disc. All filaments were tested for the same amount of time using the same normal loads. The friction behaviour was monitored and the mass wear was determined by weighting the spheres before and after each test. The research work of this paper was orientated to determine which 3D printing filament is most suitable for building different parts that come in contact with one another such as parts for creating an innovative 3D printed smart shoes sole.

1. Introduction

3D printing also known as rapid prototyping is widely used nowadays for quickly creating parts for mechanical systems [1]. The works of this paper will be focused on determining the friction coefficient and wear of different 3D printing materials. Although vast research was conducted in this area by Bellini et al [2] and Song et al [3], this paper will focus on 3D filaments produced and distributed by Zortrax, a Polish based company developing 3D printing solutions. Perepelkina et al [4] studied the friction coefficient and wear of PLA (a special type of thermoplastic derived from biomass) and ABS (the plastic that LEGO pieces are made of) materials with experimental parts being produced at 100% fill state, and concluded that it is possible to predict their tribological behaviour at this fill state. In accordance to their findings, this paper will analyse the tribological behaviour of 8 different polymers (different from the normal ABS and PLA) under a different fill state, printed on a Zortrax M200 Desktop 3D Printer. The research results will be used in determining which materials are the most suitable for building a new shoe sole. Mass printing custom fit 3D soles is considered one of the future directions in athletic shoe manufacturing and Adidas in collaboration with Carbon have already started research and production in this area (see figure 1).



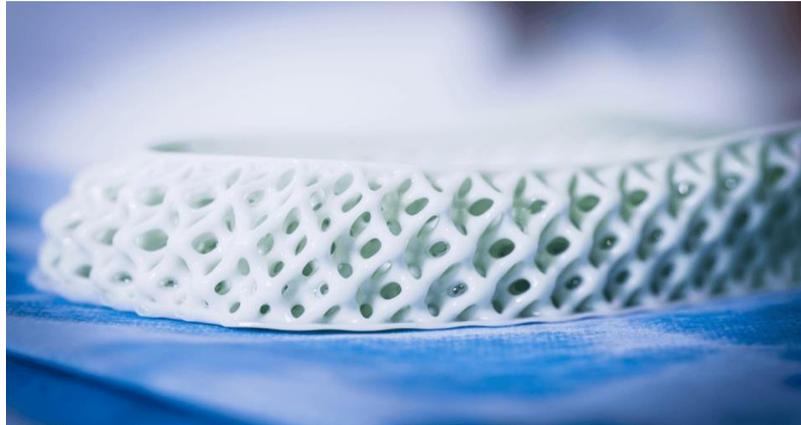


Figure 1. 3D printed shoe sole developed by Adidas and Carbon [5].

2. Sample description

For the purpose of this paper we analysed 8 different 3D printing materials that came in the form of filaments (see figure 2a) . The material filaments were the following: 1 (Z-ABS – optimal material for people who want to start 3D printing), 2 (Z-GLASS – material with a translucent structure), 3 (Z-HIPS – material designed for printing bigger parts), 4 (Z-PCABS – material with high strength and durability), 5 (Z-PETG – material resistant to acids, solvents, alkalis and salts), 7 (Z-ESD – material that provides electrostatic protection), 8 (Z-PLA PRO – material designed to reduce shrinkage in order to obtain fine details) and 9 (Z-ASA PRO – resistant to UV, humidity and heat, designed for outdoor conditions). For material number 6 (Z-ULTRAT), our sample filament broke before printing could be completed, so this material was excluded from the study. The detailed technical data sheets for all the materials can be found on the Zortrax website.

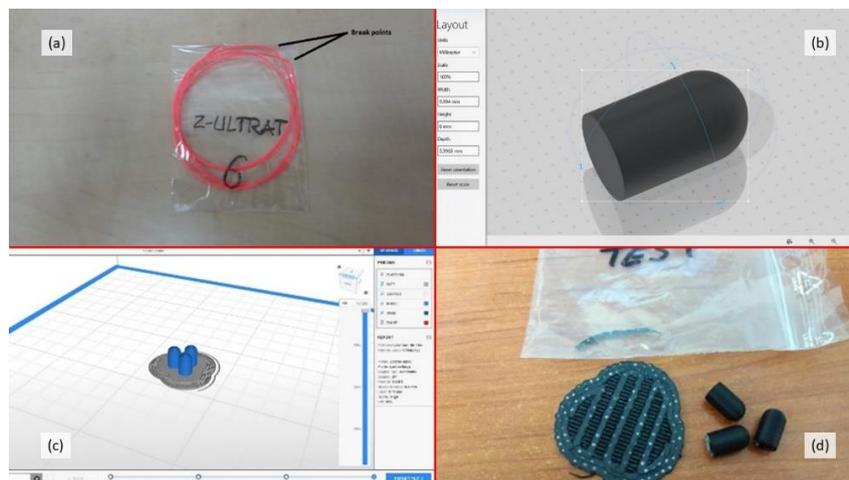


Figure 2. (a) Example of Z-ULTRAT filament (b) Pin modelled in SolidWorks and opened with Windows Print 3D (sideways orientation where width is actually the height) (c) Pre-production of 3D pins in Zortrax Z-Suite (d) Example of 3D printed test pins.

3D half inch diameter pins with a half sphere ends were modelled in SolidWorks, a 3D modelling software (see figure 2b), then added in the Zortrax Printing Software (Z-Suite) and arranged in series of

3 pins to be printed at once (see figure 2c). The pins from each material were then measured and sanded to proper dimensions in width to ensure they fit smoothly in the testing device (see figure 2d).

The technical dimensions and characteristics of the pins were the following: Height (10 mm), Diameter (6 mm), Half ball end (3 mm radius) (figure 2b). Distance from bottom to start of half ball end (7 mm). The pins were printed on a Zortrax M200 3D printed via FDM (Fused Deposit Modelling) where the filament was heated to a maximum of 290°C (depending on the materials used) and extruded through a 0.4 mm diameter nozzle. The nozzle would deposit the melted filament in a linear pattern (PATT. 0) with a layer thickness of 0.14 mm accounting for a 90% infill state for each printed object (figure 2c).

3. Experimental procedure

The scope of this paper was to determine the tribological properties of different 3D printing materials in order to draw conclusions on which of them would be more suitable in building an innovative 3D printed shoe sole. The friction coefficient as well as the wear behaviour were determined.

3.1 Determining the friction coefficient

The method used for testing the friction coefficient was the pin-on-disc method. With this method, 3 pins were placed in sockets on a disc at 100 mm from the centre (figure 3b), which in turn was placed on a metal disc, and then the disc was rotated. The speed of the rotating disc was 350 rpm (rotations per minute). Because small residue was left behind after each test, the disc was cleaned using 2 different sand papers with 1200 and 2000 granulation. The disc as well as the pins were then degreased using a degreasing solution and left to dry off leaving the contact surface smooth (figure 3a). The first load was the disc itself that accounted for a loading force of 10.17 N. After that, a first weight was added, and the total load force was 11.72 N. The second weight was added after that to increase the load force to 14.91 N, then the third to increase the load force to 17.13 N, and finally the fourth for a total load force of 18.55 N. Figure 3b shows the slots where the pins were inserted, figure 3c shows the different weights, and figure 3d shows the full test assembly.

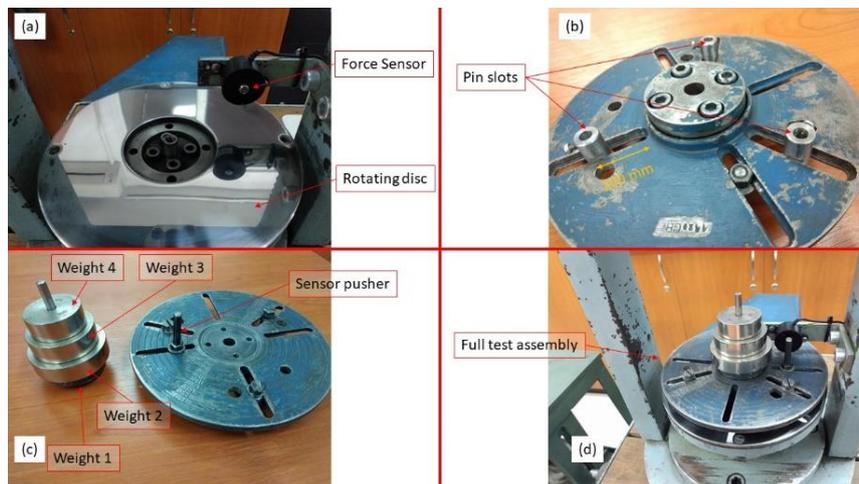


Figure 3. (a) Rotating Disc and force sensor (b) Pin Slots (c) Weights and sensor pusher (d) Full test assembly – 3 pins on disk tribometer.

3.2 Determining the wear behaviour

The wear behaviour was tested using the same test assembly as shown in figure 3d. The metal disc was rotated and the pins were placed on it with the maximum force load of 18.55 N for 5 minutes, then 10 minutes, 15 minutes and lastly 20 minutes. The pins were weighed before and after each run using with

an analytical KERN AEJ 200-4CM scale. As seen in figure 4, prominent residue was left after some runs, so the disc was cleaned with sand papers and solvent after each run. All in all, each pin sample was worn for 50 minutes in total. Photos of the end of the pins (the part that came in contact with the metal disc) were taken, using a Park System digital microscope (500 x zoom) before the start of the test and after each run. The pins were placed in the same position (in relation to the rotation angle) as to ensure micro parts don't break out so easily.



Figure 4. Residue left on disc after a wear test.

4. Results and Discussion

4.1 Friction coefficient results

Results for the friction coefficient were generated by the force sensor mounted on the test assembly. Figure 5 presents an example on how the results looked after each completed test. Table 1 shows the results for the friction coefficient constant (μ), where F_f is the friction force measured in Newtons (N) and F_n the normal loading force also measured in Newtons (N). In this relationship, $\mu = F_f/F_n$. The highlighted results were excluded from the calculation as they were too far off, while the last row (μ_a) in the table presents the average of all friction coefficients after all test runs.

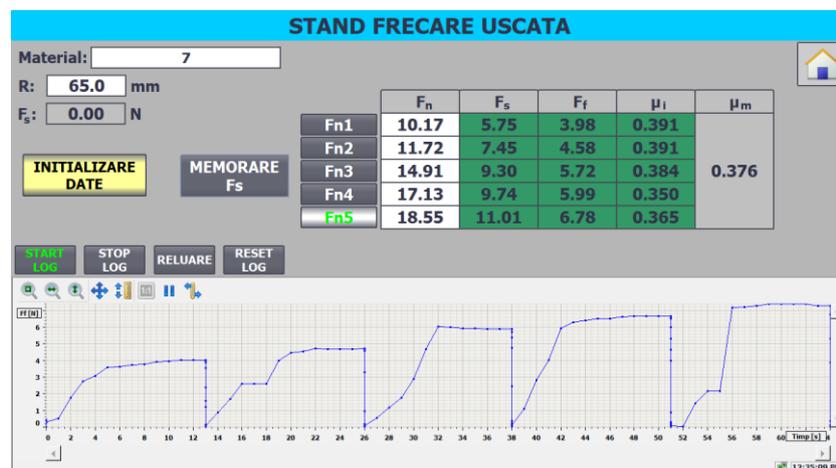


Figure 5. Example of the SIEMENS software used for the measurement.

Table 1. Results of friction coefficient test.

	1	2	3	4	5	7	8	9
F_{n1} (N)	10.17	10.17	10.17	10.17	10.17	10.17	10.17	10.17
F_{n2} (N)	11.72	11.72	11.72	11.72	11.72	11.72	11.72	11.72
F_{n3} (N)	14.91	14.91	14.91	14.91	14.91	14.91	14.91	14.91
F_{n4} (N)	17.13	17.13	17.13	17.13	17.13	17.13	17.13	17.13
F_{n5} (N)	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55
F_{r1} (N)	2.23	4.38	0.09	2.74	0.72	3.98	3.15	4.97
F_{r2} (N)	2.79	4.54	5.71	3.88	0.31	4.58	1.93	3.96
F_{r3} (N)	3.26	5.89	7.49	5.09	2.54	5.72	4.32	7.04
F_{r4} (N)	5.07	6.39	8.76	8.4	5.73	5.99	5.16	8.02
F_{r5} (N)	5.68	7.77	9.07	0.59	0.37	6.78	0.03	8.67
μ₁	0.22	0.431	0.009	0.269	0.07	0.391	0.31	0.489
μ₂	0.238	0.387	0.488	0.331	0.026	0.391	0.165	0.338
μ₃	0.219	0.395	0.502	0.341	0.17	0.384	0.29	0.472
μ₄	0.296	0.373	0.511	0.49	0.335	0.35	0.301	0.468
μ₅	0.306	0.419	0.489	0.032	0.02	0.365	0.002	0.467
μ_a	0.256	0.401	0.497	0.357	0.071	0.376	0.266	0.446

4.2 Results of wear behaviour tests

The results shown in table 2 present the initial mass (M_i) of the pins and their mass, measured in grams (g), after 5 minutes of wear (M_1), 10 minutes of wear (M_2), 15 minutes of wear (M_3) and 20 minutes of wear (M_4). The graph in figure 6 presents the same wear behaviour in a visual manner, while figure 7 shows a time lapse of one of the pins to illustrate how the wear behaviour looks like.

Table 2. Results of wear behaviour tests.

	1	2	3	4	5	7	8	9
M_i (g)	0.7157	0.8753	0.6826	0.7426	0.9724	0.8000	1.0272	0.8277
5 minutes - M₁ (g)	0.7114	0.8749	0.6809	0.7426	0.9712	0.7992	1.0270	0.8268
10 minutes - M₂ (g)	0.7112	0.8746	0.6787	0.7419	0.9712	0.7958	1.0241	0.8154
15 minutes - M₃ (g)	0.7110	0.8746	0.6778	0.7416	0.9706	0.7927	1.0231	0.8042
20 minutes - M₄ (g)	0.7107	0.8746	0.6764	0.7405	0.9700	0.7860	1.0219	0.7702
Total wear (%)	0.6986%	0.0799%	0.9082%	0.2827%	0.2468%	1.75%	0.5159%	6.9469%

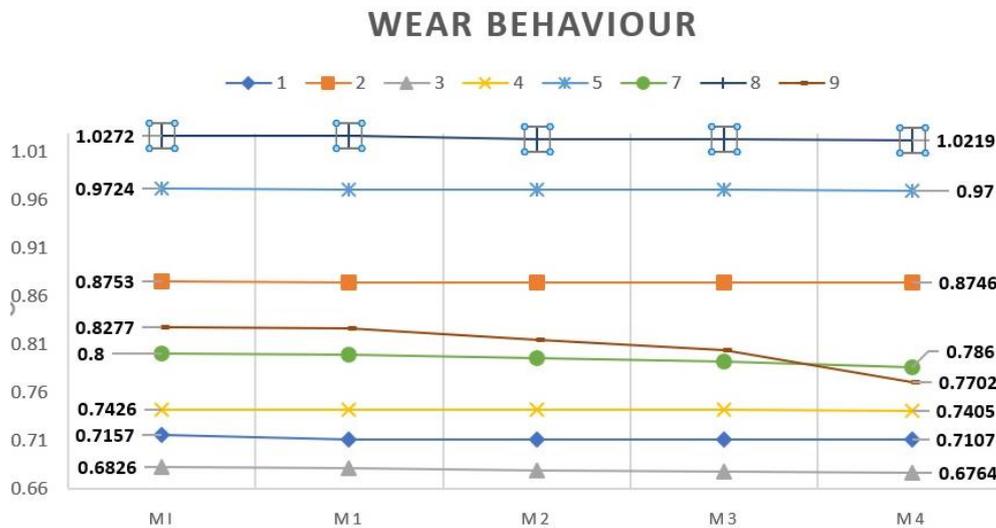


Figure 6. Graph of wear behaviour tests.



Figure 7. Time-lapse of wear behaviour on sample 8 and wear curve.

4.3 Discussions

The paper aims to determine the friction coefficient and wear behaviour of different 3D filaments in contact with a metallic disc. The method used for testing was the pin-on-disc method, where 3D half inch diameter pins with a half sphere end were printed out of the different filaments and placed on a rotating metal disc made out of C-45 steel.

The experiment was performed on 8 samples fabricated from different 3D printing materials, in room temperature conditions and ambient humidity.

The scope was to measure the friction coefficient and to evaluate the wear behaviour. The highest wear percentage (6.9469%) was determined in the case of sample 9 (Z-ASA PRO) followed by sample 7 (Z-ESD) and the lowest wear percentage (0.0799%) corresponds to the sample 2 (Z-GLASS), followed by sample 5 (Z-PETG). Figure 8 presents the comparative wear behaviour of the sample 9 (figure 8a) and sample 2 (figure 8b).

Moreover, in the case of some samples the material was removed during the wear tests while in other samples, although wear was clearly visible, the materials was only exfoliated without complete material removal (see figure 7).

The wear behaviour observed during the experiments was not in direct concordance with the friction coefficient of the different filaments. The highest friction coefficient was determined in the case of sample 3 (Z-HIPS) followed closely by sample 9 (Z-ASA PRO). The lowest friction coefficient was determined for sample 5 (Z-PETG) with a medium wear percentage of 0.2468% .

The wear behaviour observed during the experiment of sample 2 (Z-GLASS) is not in concordance with the measured friction coefficient, because a small wear percentage of 0.0799% was determined with relatively high friction coefficient of 0.401.

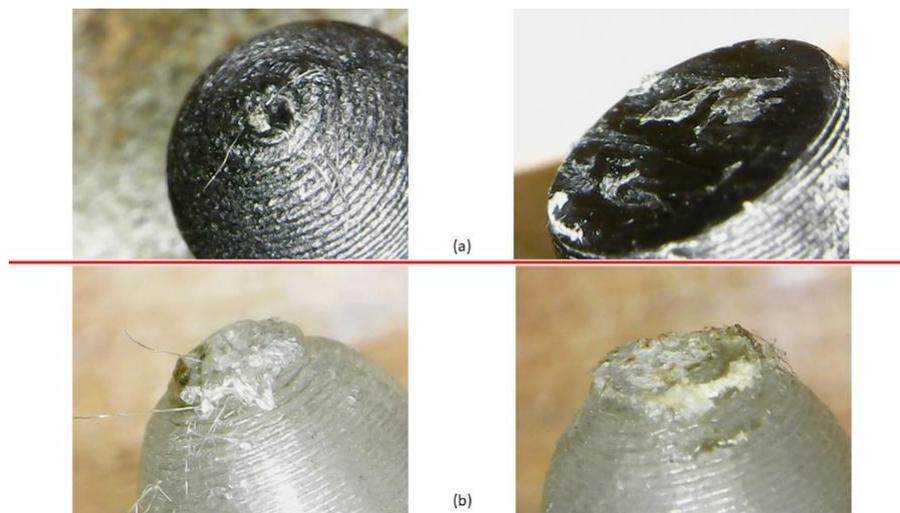


Figure 8. Wear behaviour in the case of (a) Z-ASA PRO and (b) in the case of Z-GLASS.

5. Conclusion

Product development based on different 3D printing materials is of growing interest worldwide. In order to produce reliable products, the materials' mechanical and tribological properties must be well known. This paper was orientated to investigate the tribological behaviours of some selected 3D printing materials. As a function of materials properties different friction and wear behaviours were determined. Depending on the applications, the product developers can choose which kind of materials correspond to the manufacturing needs.

In conclusion, if the interest is to develop soles with low wear behaviour and high friction, one recommendation is to use the Z-GLASS material, if the mechanical behaviour corresponds with the product requirements. If one needs a balance between friction and wear (like in the day-to-day shoes), then materials corresponding to the sample 1 (Z-ABS) and 8 (Z-PLA PRO) are recommended. For soles requiring low friction (for example sportive dancing) material nr 5 (Z-PETG) is recommended. If the wear is not considered a pressing issue, for good friction, material number 3 (Z-HIPS) is recommended.

6. References

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