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INVESTIGATION ON PRODUCTION PARAMETERS OF ADDITIVELY MANUFACTURED ABS POLYMER GEARS

Abstract. *The amount of wear and the load-bearing capabilities are important factors in the lifespan performance of gears. And those factors can be influenced by different 3D printing parameters in production. The objective of the research work was to analyze the material behaviour of printed Acrylonitrile butadiene styrene (ABS) polymers for gears according to production parameters. Each printed specimen was tested several times and summarised the results by determining the average values. While the wear performance of the samples was highly influenced by the "Layer height" parameter, the load-bearing capacities of the printed samples were highly influenced by the amount of the "Infill pattern" production parameter. Finally, based on the carried out experimental tests, the ideal 3D printing parameters were decided to provide the highest load-bearing capacity and the lowest friction coefficient under compressive forces for 3D printed ABS polymer gears.*
Keywords: *3D printing; ABS; FDM and printing parameters.*

1. INTRODUCTION

Polymer gears have replaced metal gears in a variety of industrial applications in recent times. Because of the advantages that polymer gears have over metal gears, their use has significantly increased in the last few years. Some examples of plastic gears field applications include the automobile industry, office equipment, and household utensils, as well as food and textile machinery [1–4]. Polymer gears offer some advantages compared to metal gears, particularly, in terms of their high specific mechanical properties (high size-weight ratio), good tribological efficiency (low friction coefficient, self-lubrication), high resistance against impact loading due to the elasticity of the material, ability to absorb and damp vibration, etc.
On the other hand, polymer gears have several disadvantages, such as a reduction in load-carrying capability and low operating temperatures if compared to metal gears, relatively high dimensional variations due to temperature and humidity conditions, etc. [5]. In addition, unlike metal gears, polymer gears are usually run with no lubricant [6].

Nowadays polymer gears are mainly produced by Additive Manufacturing (3D printing) technologies because this technology is quite different from traditional techniques, and it offers so many advantages comparing with others such as the digital nature of the fabrication process.

Additive manufacturing (AM) also known as 3D printing, is getting more interest because of the significant increase in the requisition for high-performance materials and increased functionalities and complexities in a geometrical design.

In the last years, additive manufacturing has been considered an effective production technology, and it got a major position in the manufacturing sector with the development of technology. The fundamental principle of this technology is that a model initially created layer-by-layer using a 3D Computer - Aided Design system, can be produced directly without the requirement for process planning [2, 7–11].

There are many kinds of 3D printing technologies on the market, with their own capabilities and limitations. Among them all, the Fused Deposition Modelling (FDM) technique appears to be more practical for general use because it produces the objects with the filament itself while in other 3D printing techniques the use of resin-based material is a necessity [12–14]. In this method, the polymer filament is pushed onto a surface through a heated nozzle, at first it melts, and then solidifies upon touching the surface, and thus a structure is built up layer by layer [15].

There are several printing parameters such as temperature, infill pattern, layer height, printing speed, etc. that should be defined before the FDM production process. The mentioned production parameters can influence the accuracy, material and mechanical properties of the printed part, and printing time.

Because of the mentioned facts above, load-carrying capability and amount of wear are critical factors in the production process of polymer gears, and several production parameters should be investigated for this purpose.

The current paper gives a summary of the analysis carried-out on additively manufactured acrylonitrile butadiene styrene polymers used for gears, characterizing the material behaviour with ball-on-disk and compression laboratory tests.

2. SAMPLE PROCESSING

The specimens (Figure 1) were produced from ABS thermoplastics by using the "Ultimaker Original +" 3D printer (Figure 2) to perform experimental wear tests. The same 3D printer was used to print all the specimens for the current research work.

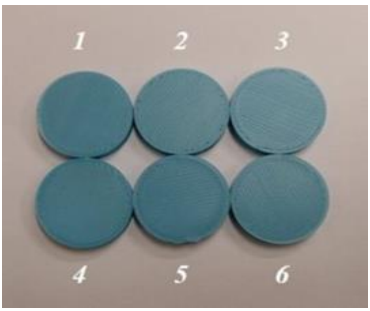

Figure 1 – 3D printed ABS samples for ball-on-disk test

Figure 2 – Ultimaker Original +" 3D printer [16]

From Table 1 it is seen, that ball-on-disk test samples are produced with different processing parameters, providing the possibility to investigate the effect of the layer height (0.2 mm or 0.4 mm), the printing speed (30; 50 or 80 mm/s), and the number of base layers and top layers (1; 3 or 5).

Table 1 – Printing parameters of the 3D printed specimens for ball-on-disk wear tests

Material	Sample No	Temp. (^{0}C)	Layer height (mm)	Printing Speed (mm/s)	Number of Contours	Base layers	Top layers	Infill pattern, %
ABS	1	220	0.2	50	2	3	3	100
	2		0.4	50		3	3	100
	3		0.2	30		3	3	100
	4		0.2	80		3	3	100
	5		0.2	50		1	1	25
	6		0.2	50		5	5	50

The samples (Figure 3) for the experimental compression tests were produced from ABS thermoplastic in a small cube form with dimensions of 10x10x10 mm.

Different printing parameter combinations (illustrated in Table 2) were used to print all the samples, providing the possibility to investigate the influence of the temperature (190; 210; 220 or 230 °C), layer height (0.2 mm or 0.4 mm), Infill pattern (25; 50 or 100 %). Every 3 samples were produced with the same material and the same printing parameters to determine the average test results.

Figure 3 – 3D printed ABS samples for compression test

Table 2 – The used 3D printing parameters of ABS samples for compression test:

Material	Sample No.		Temp. (^{0}C)	Layer height (mm)	Printing Speed (mm/s)	Number of Contours	Base layers	Top layers	Infill pattern, %
ABS	1	1-1.1-1.2	210	0.2	50	2	3	3	100
	2	2-2.1-2.2	220	0.2					100
	3	3-3.1-3.2	230	0.2					100
	4	4-4.1-4.2	220	0.4					100
	5	5-5.1-5.2	220	0.2					25
	6	6-6.1-6.2	220	0.2					50

3. MATERIAL TESTING METHODS

Ball-on-disk test

The standardized ball-on-disk test method is particularly well suited to analyze the relationships between the wear resistance, wear mechanisms, and loading parameters such as sliding velocity, contact pressure, and environmental conditions.

The specimens were cleaned and dried prior to the testing and measuring processes. Non-chlorinated, non-film-forming cleaning agents and solvents were used to remove all dirt and foreign substance from the specimens. Then the required parameters were set and started the test. When the desired number of revolutions was reached, the test was stopped. As the last step, the specimens were removed and cleaned off from any loose wear debris [17]. Sometimes this last operation is neglected if the wear debris morphology would be analyzed that provides valuable information about the wear mechanism.

CETR – UNMT1 Universal Micro-Nano Materials Tester (Figure 4) was used to perform ball-on-disk sliding friction tests on specimens. Several pre-tests were performed with different loading conditions to find better test parameters for the target tests. As a result, the most purposeful testing conditions were defined and the experimental wear tests were carried out with the following variables:

− Normal load, F = 10 N;
− Time, t = 180 min;
− Sliding velocity, v = 25 mm/s;
− Rotational speed, n= 79.6 1/min.

Figure 4 – CETR – UNMT1 Universal Micro-Nano Materials Tester

Compression test

In the compression testing technique, the samples are compressed between two platens. During the test, an extensometer and load cell equipment are used for measuring displacement and force. This type of testing technique is useful to study a material or mechanical part load bearing capacity under compressive loading [18]. A schematic diagram of the compression testing machine is illustrated in Figure 5.

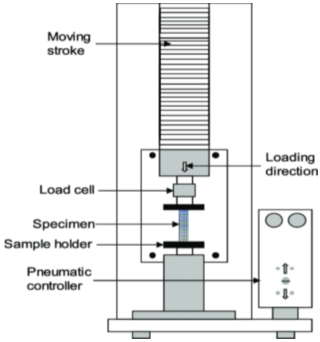

Figure 5 – Schematic diagram of the compression testing machine [19]

4. EXPERIMENTAL RESULTS AND DISCUSSION

Based on the performed ball-on-disk wear tests, the change in friction coefficient with respect to the sliding distance graphs was analyzed. Typical friction coefficient vs. sliding distance diagrams are shown in Figure 6. The diagrams show a steady-state character, i.e., the friction coefficient values are stabilized in the second half part of the total sliding distance. According to the gathered diagrams, the steady-state friction coefficient values (μ_{ss}) were determined as the average of those measured on the last 20% of the sliding distance, i.e., in the stabilized region.

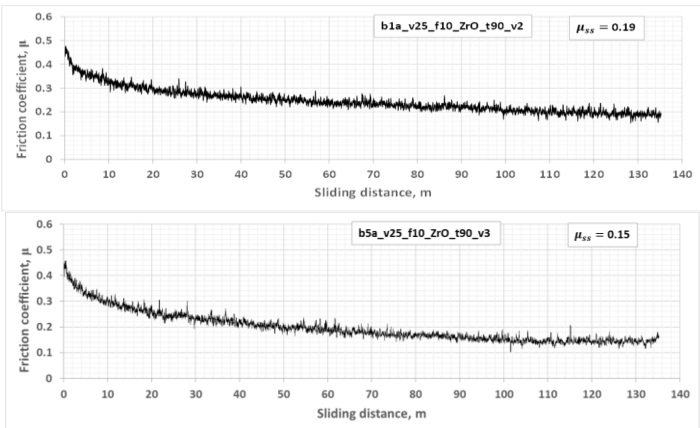

Figure 6 – Typical friction coefficient diagrams obtained during ball-on disk wear tests

The wear test results determined in the above-mentioned way, are presented in Table 3. Comparison of the measured friction coefficient data and assessing the general trend is easier by visualizing them in a diagram. While Figure 6 provides insight into the friction behaviour of the produced samples made of ABS plastics along with the whole sliding distance, Figure 7 gives information on the friction coefficient values developed at the end of the total sliding distance.

Table 3 – Steady-state friction coefficient values obtained from the ball-on-disk wear test

Material	File name (wear track)	Ball-on-disk test results			
		Final friction coefficient μ_{ss}	Average	Standard deviation, SD	Var. coeff. %
ABS	ABS_1_v1	0.168	0.181	0.019	10.5
	ABS_1_v2	0.194			
	ABS_2_v1	0.259	0.257	0.002	0.8
	ABS_2_v2	0.255			
	ABS_3_v1	0.191	0.192	0.002	0.8
	ABS_3_v2	0.193			
	ABS_4_v1	0.209	0.212	0.005	2.1
	ABS_4_v2	0.215			
	ABS_5_v2_2	0.122	0.133	0.017	12.4
	ABS_5_v3	0.145			
	ABS_6_v1	0.213	0.212	0.002	1.1
	ABS_6_v2	0.210			

By analysing the ball-on-disk experimental wear tests, the following establishments can be made regarding the influence of the technological parameters of the 3D printing on the friction behaviour of the ABS plastic samples:

- At the applied total sliding distance, the lowest friction coefficients were achieved for samples ABS_5_2_2 and ABS_5_3 and ABS_1_1, μ_{ss} = 0,122; 0,145 and 0,168 respectively.
- The less favourable friction behaviour was shown by the ABS_2_1 and ABS_2_2 samples.
- Regarding the printing parameters, the most unfavourable friction conditions occurred when the layer height was twice as high, i.e. 0.4 mm.

The friction coefficient curve for ABS_2_1 and ABS_2_2 decreases monotonically in the first half of the total sliding distance, but in the second half of the wearing test the friction coefficient values show an unusual and significant increase that is characteristic for no other samples. A possible explanation for this can be that the higher layer height adversely affected the wear behaviour, e.g., by modifying the layer structure and stiffness, making the surface layer more sensitive to damage, thus the resulting wear debris increased the value of the coefficient of friction.

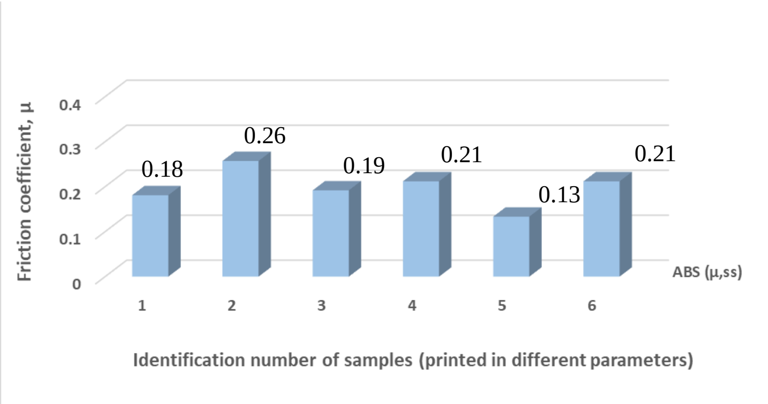

Figure 7 – Comparison of the steady state friction coefficient (μ_{ss}) values measured on the ABS samples

Based on the executed tribological tests, the processing parameters of the 3D printing, which provides the lowest friction coefficient, were determined as below.

- Temperature: 220 °C
- Layer height: 0.2 mm
- Printing speed: 50 mm/s
- Number of Contours: 2
- Base Layers: 1-3
- Top Layers: 1-3
- Infill pattern: 100%

In addition, compression laboratory tests were carried out on the 18 samples, and the maximum compressive forces were determined and summarized by calculating their average values for each sample group (illustrated in Table 4). Figure 8 shows typical force vs. displacement diagrams recorded during the compression tests to evaluate the effect of the 3D printing parameters on the test results.

Table 4 – F_1 and F_2 maximum compressive force values for ABS thermoplastics

Material	Sample No.		Compression test results			
			F_1 maximum compressive force (at 0.5 mm displace-ment or first peak point), N	Average	F_2 maximum compressive force (at the last peak point), N	Average
ABS	1.	1	5900	5600	9801	9167
		1.1	5501		9000	
		1.2	5400		8700	
	2.	2	5900	5667	8900	8501
		2.1	5700		8400	
		2.2	5400		8201	
	3.	3	5400	5567	8001	8201
		3.1	5600		8101	
		3.2	5700		8501	
	4.	4	4801	4668	9302	9234
		4.1	4602		9302	
		4.2	4601		9100	
	5.	5	2802	2735	2201	2367
		5.1	2702		2400	
		5.2	2701		2500	
	6.	6	3201	3301	3001	3767
		6.1	3400		4100	
		6.2	3301		4200	

Figure 9 was created regarding the average of the maximum compressive force values that were determined for 0.5 mm displacement or the first peak point in Figure 8. It can be clearly seen in Figure 9 that the highest average compressive force (F_1 = 5667 N) was calculated on sample group number 2 (2; 2.1; 2.2). An additional observation is that the maximum compressive forces for the sample groups number 5 and 6 decrease significantly. A possible explanation for this can be the decrement of the infill pattern parameter of the samples. The lower infill in percentage makes the structures sensitive to failure under compressive forces.

It can be established that 3D printing parameters have a significant influence on the load-bearing capacity of ABS thermoplastics. The difference between the highest and lowest average maximum compressive force values reaches 48% of the highest one.

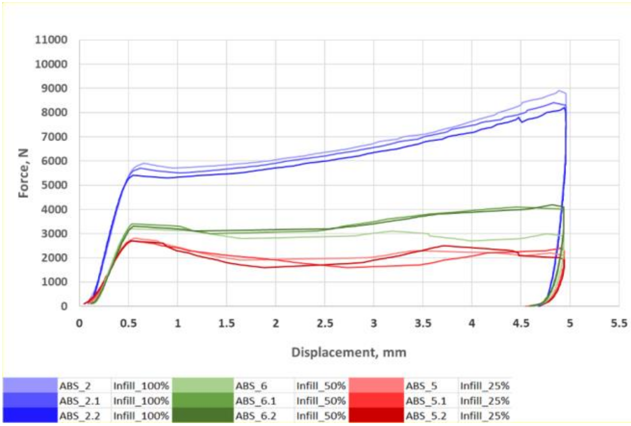

Figure 8 – The effect of "Infill pattern" parameter on load-bearing capability of samples

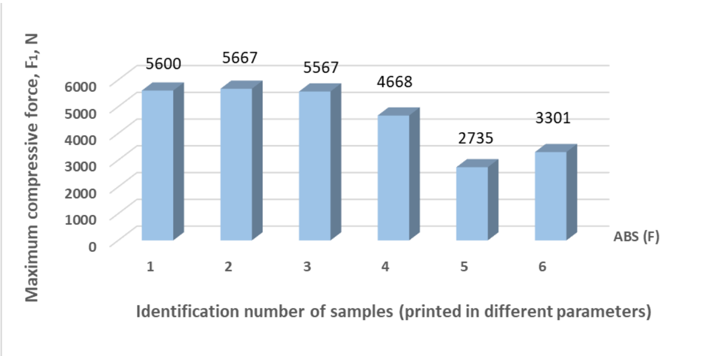

Figure 9 – Comparison of the average of F_1 maximum compressive forces

According to the compression test results, the following printing parameters presented the best results providing the highest load-bearing capabilities.

- Temperature: 220 °C
- Layer height: 0.2 mm
- Printing speed: 50 mm/s
- Number of Contours: 2
- Base Layers: 3
- Top Layers: 3
- Infill pattern: 100%

5. CONCLUSIONS

The objective of the current research work was to investigate the influence of the printing parameters on the material's behaviour of ABS polymers used for the 3D-printed gears by characterizing the material with ball-on-disk and compression tests. in order to define the load-bearing capability and wear performance.

In total, six specimens for the wear and eighteen specimens for the compression tests were printed by using the „Ultimaker Original +" 3D printer from (ABS) thermoplastic. All the specimens were printed with different printing parameter combinations to analyze their influences on the sample behaviour. For the ball-on-disk wear tests, the analyses were carried out on a variety of specimens, and the friction coefficient vs. sliding distance curve was compiled using the obtained wear test data. As a result, for the applied total sliding distance, the lowest steady state friction coefficients were achieved for sample ABS_5, $\mu_{ss} = 0.133$ as average.

Another very important factor for the gears is the load-bearing capability of the printed samples, which was investigated by the compression experimental testing method. The investigations were performed on the recorded compression test data to analyze the influence of different printing parameters on the load-bearing capabilities of printed samples. Temperature and layer height printing parameters had a measurable, but slighter influence, while the infill pattern parameter proved to have the highest effect on the load-bearing capabilities of the printed ABS polymers. According to the test results, sample group 2 could bear the highest average maximum compressive force $F_1 = 5667$ N.

As a summary, based on the executed tribological tests, the best 3D printing parameters were determined to provide the lowest friction coefficient and the highest load-bearing capacity under compressive forces for additively manufactured ABS polymer gears. These ideal 3D printing parameters are, as below:

- Temperature: 220 ℃
- Layer height: 0.2 mm
- Printing speed: 50 mm/s
- Number of Contours: 2
- Base Layers: 3
- Top Layers: 3
- Infill pattern: 100%

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ДОСЛІДЖЕННЯ ВИРОБНИЧИХ ПАРАМЕТРІВ АДИТИВНО ВИГОТОВЛЕНИХ АБС-ПОЛІМЕРНИХ ЗУБЧАТИХ КОЛІС

Анотація: *Величина зношування та несуча здатність є важливими факторами, що впливають на термін служби зубчастих передач. І ці чинники можуть впливати різні на параметри 3D-друку у виробництві. В останні роки адитивне виробництво вважалося ефективною технологією виробництва, і з розвитком технологій воно зайняло важливе місце у виробничому секторі. процесу. Мета дослідження полягала в тому, щоб проаналізувати поведінку надрукованих акрилонітрил-бутадієн-стирольних (АБС) полімерів для зубчастих коліс залежно від виробничих параметрів. Кожен надрукований зразок тестували кілька разів і підсумовували результати, визначаючи середні значення. У той час як на зносостійкість зразків сильно впливав параметр «Висота шару», на несучу здатність друкованих зразків, сильно впливала величина виробничого параметра «Шаблон заповнення». Нарешті, на основі проведених експериментальних випробувань було прийнято рішення про ідеальні параметри 3D-друку, щоб забезпечити найвищу несучу здатність і найнижчий коефіцієнт тертя при стискаючих зусиллях для зубчастих коліс, надрукованих на 3D-принтері з АБС-пластика. Усі зразки були надруковані з різними комбінаціями параметрів друку, щоб проаналізувати вплив на поведінку зразка. В результаті, для прикладеного повного шляху ковзання найнижчі коефіцієнти стаціонарного тертя досягнуто для зразка ABS_5,* $\mu_{ss} = 0{,}133$ *в середньому. Іншим дуже важливим фактором для зубчастих коліс є несуча здатність друкованих зразків, яка була досліджена методом експериментальних випробувань на стиск. Параметри друку температури та висоти шару мали сумірний, але менший вплив, у той час як параметр малюнка заповнення справив найбільший вплив на несучу здатність надрукованих АБС-полімерних зразків. За результатами випробувань група зразків 2 витримала найбільше середнє максимальне зусилля* $F_1 = 5667$ *Н.*

Ключові слова: *3D-друк; АБС-полімер; FDM та параметри друку.*