PRODUCTION OF FIBER AS AN INPUT MATERIAL FOR THE 3D PRINTING PROCESS

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DOI: 10.17973/MMSJ.2021_6_2021031

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Additive manufacturing, also known as 3D printing, is the process of joining organic, ceramic, polymer, metal and others materials. Most often used as input material are the ABS and PLA plastics. A large number of plastic products is constantly generated by industry, which beckons the idea how to manufacture these products in more environmentally friendly way. This paper deals with the possibility of producing a 3D printing fiber from a granular PLA material Ingeo 2003D with the addition of a mixture of color powder pigment and fiber from the selected PLA material with a glass powder filler. The production was carried out using the FilaFab PRO EX350 device, which is designed for fiber extrusion for 3D printing technology. The aim of the experiment was the creation of new materials in the form of fibers and their mutual comparison in tensile tests with commercially available materials intended for 3D printing.

KEYWORDS

3D printing, FilaFab PRO EX350, fiber production, filler, admixture, PLA Ingeo 2003D.

1 INTRODUCTION

Special attention nowadays is paid to 3D printing innovations, mainly from a technological point of view [Gibson 2015]. Along with machine learning and artificial intelligence, it is one of the leading technologies in various industries [Poor 2018]. A significant advantage of using this technology is mainly the diversity of designs, minimization of production waste and new products prototyping speed [Maksimov 2016]. The main advantages of this technology have also been summarized by Ngo et al. [Ngo 2018] in their paper, which also provided a comprehensive overview of 3D printing methods, materials and of the development of revolutionary applications of this advanced production technology in various areas of industry. Although 3D printing has long been used in architecture and various industries for the production of prototypes and various models, it has dominated other areas such as medicine, art, design, science, etc. in the last decade only. An example is the book by Khademhosseini [Khademhosseini 2018], which deals with 3D bioprinting and currently used biomaterials, as well as the latest advances in this field of research and development. It can be stated that no other technology in the world gives as much design freedom and a high level of detail as 3D printing, the current innovations in which are also presented in more detail in the book by Singh et al. [Singh 2018]. With additive manufacturing, it is possible to design and manufacture parts that perfectly meet all our needs. An article by Dey et al. [Dey 2019] deals in more detail with the influence of parameters and their optimization on the quality of parts production by the FDM technology. Additive production is the common name for the technology of producing 3-dimensional objects by applying and joining materials layer after layer. Compared to traditional mechanical engineering production, it enables the production of complex geometry products, good shape flexibility, shorter time required for component development, high material utilization [Kascak 2021]. The mechanical properties achieved by the product are comparable to or even better than those achieved by traditional production [Dobransky 2019a]. In their study, Yuang et al. [Yuang 2019] addressed the field of polymeric composite materials, their powder preparation for additive production by selective laser sintering technology of polymeric, metallic, ceramic and composite materials, describing the importance of polymer composites for powder-using additive production.

This paper deals in more detail with the process of producing fibers intended for additive technology using the FilaFab PRO EX350 device. The main task of research is to develop new materials, with the aim of gradually replacing commonly used materials, as well as the production of components and parts from environmentally friendly materials. This study aims to partially contribute to the increase of environmental friendliness of additive production, the production of experimentally produced fibers using materials that do not have an adverse impact on the environment [Dobransky 2016b].

2 PROCEDURE OF PREPARATION AND COURSE OF THE PRODUCTION PROCESS

The initial stage of new materials production with the addition of additives and fillers intended primarily for 3D printing required the preparation of the necessary material and equipment. This phase included the procurement of an experimental Ingeo 2003D granular PLA material (granule size 5-7 mm), a FilaFab Pro EX350 fiber extruder, a digital hygrometer, an external fiber cooling device, a winder, a tachometer to determine the speed of the device and a caliper for control measurement of the diameter of the fiber produced [Baron 2016]. The experiment was conducted under laboratory conditions at the room temperature of 21 °C and an air humidity of 54 %.

The manufacturing process consisted of the gradual addition of Ingeo 2003D granules to the hopper of the FilaFab Pro EX350 together with an admixture/filler according to a specified formula. Under pressure and temperature, the PLA material and admixture/filler were mixed into a homogeneous mass, which was then extruded through an extruder nozzle with a desired fiber size of 1.75 mm ± 0.05 mm in diameter. The formed fiber was cooled by an external ventilation device to speed up its solidification and use. The solidified fiber was then wound on a spool using a winder. Once produced, the fiber was checked visually and also with a measuring device to examine whether it has the required diameter and whether its quality meets the 3D printing requirements [Stejskal 2019]. The created fiber could be used immediately after having been produced in the 3D printing process of components [Guo 2010].

Subsequently, the fibers were used to create test specimens printed on a commercial Creality Ender 3D printer to test and determine mechanical properties using tensile tests. Tab. 1 shows the combinations of materials and admixtures/fillers that were used in the new fiber formula.

Table 1. Combinations of materials for fiber production

Fiber type	Material	Admixture/filler
Color fiber	Ingeo 2003D	Color powder pigment
Glass fiber	Ingeo 2003D	Glass powder

2.1 *Fiber produced from Ingeo 2003D with a color pigment admixture*

This fiber production focused on the processing of fiber from the selected granular PLA material Ingeo 2003D with a color powder pigment admixture. The color powder pigment (blue powder food dye, Detecha brand) was selected to retain the ecology of the selected PLA material. The granular PLA and the color powder pigment were mixed in a special vessel. Once the components of the material were mixed, the material was placed in the hopper of the FilaFab Pro EX350 device for fiber production. Through the correct settings of the device's parameters (temperature and pressure), a homogeneous mixture was formed and extruded through the nozzle of an extruder with the size matching that of the desired fiber, with a diameter of 1.75 mm ± 0.05 mm. The produced color fiber was cooled at the outlet from the extruder by an external ventilation device and wound on the spool of the winder. Tab. 2 shows the ratios of the input materials used for the production of the color fiber with the admixture of color powder pigment and the extruder settings used in the experiment.

Table 2. Ratio of materials entering the color fiber production

Type	Granulate PLA Ingeo 2003D	Blue powder pigment
Quantity	100 g	2.5 g
Melting point	160 - 165°C	
Extruder speed	6.5 rpm	
Percentage ratio	97.50 %	2.50 %

2.2 *Fiber produced from Ingeo 2003D with an admixture of glass powder*

Further production focused on the production of glass fiber from Ingeo 2003D granulate with an admixture of glass powder. The advantage of glass fiber is its lightness thanks to the glass powder, which consists of microbeads. Glass beads consist of chemically stable, slightly alkaline and water-insoluble borosilicate glass. Particles with a nominal density of 0.2 g/cm^3 and an average particle size of 65 µm are used. In the glass fiber production, the formula of 100 g Ingeo 2003D to 0.312 g glass powder was used. The mixed materials were placed in the extruder hopper preheated to 170 °C for 30 minutes prior to the experiment. As a result, the PLA material melted and bonded with the glass powder. Only then did the extruder engine start and the temperature was reduced to 165 °C. The extruded fiber acquired a visible gray color, and after the final inspection, the fiber produced was suitable for further processing in 3D printing.

3 TESTING AND EVALUATION OF THE MATERIAL SPECIMENS

Thirty test specimens were made from the examined samples of materials to test the fibers, which were subjected to tensile testing and a comparison of the mechanical properties they achieved [Valicek 2017]. Ten specimens from each material were created, with 20 test specimens made from fibers made in the FilaFab Pro EX350 and 10 specimens made from commercially available fibers purchased from 3D printing material vendors. The test specimens were prepared according to the STN 527 standard [Panda 2018]. Tab. 3 shows experimental test specimens' combinations.

Table 3. Types and designation of test specimens

Name	Type of material	Producer
1-10/A	Color fiber	Commercial producer
1-10/B	PLA + color powder pigment	Experimental material
1-10/C	PLA + glass powder	Experimental material

All tensile tests were conducted on an Instron 5982-100kN shredder. The tensile test was done at a constant device speed of 20 mm/min and the values obtained were gradually recorded for the resulting loads of the specimen tested. The test involved a tensile test, which examines the effect of external forces on the tested specimen's deformation [Straka 2016]. It consists of attaching the test specimen between the jaws of the test rig, where the force applied onto the test specimen is subsequently increased until the specimen's integrity is broken. The magnitude of the force F is determined experimentally, by means of an extensometer placed on the body. The output is a graph of dependence values of stress and deformation properties of the specimen tested [Murcinkova 2017]. A tensile diagram was used to evaluate the test specimens, from which information was obtained on the elongation of the test specimen as a result of the loading force.

3.1 *Group A test specimens – color PLA (commercial material)*

Tab. 4 shows the results of tests carried out on 10 color PLA test specimens of commercial material.

Table 4. Tensile test results – Group A test specimens

	Maximal force [N]	Tensile stress at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]	Speed [mm/min]
1	679.49	79.94	1.26	666.87	78.46	3.47	20
2	958.14	112.72	2.61	865.35	101.81	5.38	20
3	932.47	109.70	2.22	841.57	99.01	5.38	20
4	814.15	95.78	2.00	620.33	72.98	3.84	20
5	809.96	95.29	1.76	772.39	90.87	3.61	20
6	913.63	107.49	2.28	831.36	97.81	4.33	20
7	800.16	94.14	1.95	712.94	83.88	3.47	20
8	877.95	103.29	1.87	799.52	94.06	4.09	20
9	860.25	101.21	1.72	783.06	92.13	4.02	20
10	917.60	107.95	2.12	833.45	98.05	4.13	20

Fig. 1 is a graphical plot representing the dependence of the tensile stress on the relative deformation for the group A of tested specimens. Fig. 2 illustrates the test specimens torn in tensile tests.

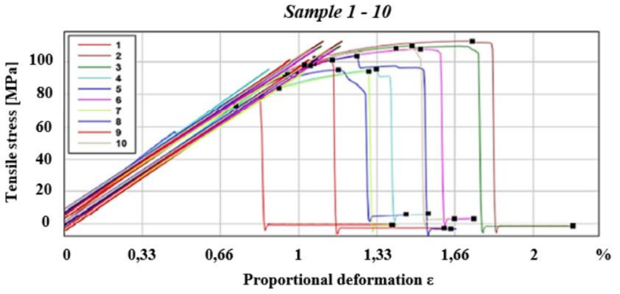

Figure 1. Graphical dependence of tensile stress on proportional deformation - Group A test specimens

Figure 2. Torn test specimens of Group A

3.2 *Group B test specimens – color PLA (noncommercial material)*

Ten color PLA test specimens of experimental material were tested. The results from the tensile tests of Group B test specimens are shown in Tab. 5.

Table 5. Tensile test results – Group B test specimens

	Maximal force [N]	Tensile stress at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]	Speed [mm/min]
1	1672.23	196.73	2.16	1565.60	184.19	4.26	20
2	989.64	116.43	1.59	931.20	109.55	3.57	20
3	1425.22	167.67	2.00	1336.59	157.25	3.61	20
4	1272.50	149.71	1.87	1199.74	141.15	3.21	20
5	1554.63	182.90	1.85	1482.11	174.37	3.13	20
6	1566.32	184.27	2.10	1462.63	172.07	3.69	20
7	878.94	103.40	1.71	834.04	98.12	3.73	20
8	999.76	117.62	2.14	924.62	108.78	3.84	20
9	1261.55	148.42	2.45	1151.52	135.47	5.07	20
10	1224.22	144.03	2.33	1120.59	131.83	4.81	20

Fig. 3 is a graphical plot representing the dependence of the tensile stress on the proportional deformation for the group A of tested specimens. Fig. 4 illustrates the test specimens torn in tensile tests.

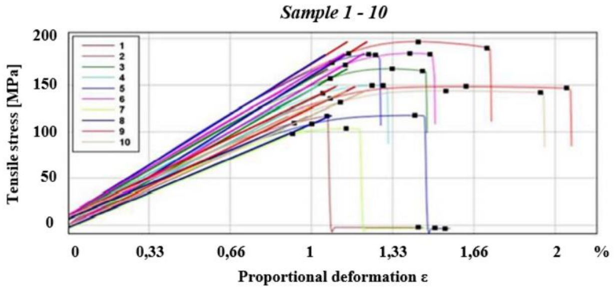

Figure 3. Graphical dependence of tensile stress on proportional deformation - Group B test specimens

Figure 4. Torn test specimens of Group B

3.3 *Group C test specimens – PLA with glass powder admixture (noncommercial material)*

Ten PLA test specimens with a glass powder admixture of experimental material were tested. The results of the tensile tests of Group C test specimens are shown in Tab. 6.

Table 6. Tensile test results – Group C test specimens

	Maximal force [N]	Tensile stress at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]	Speed [mm/min]
1	112.24	13.20	1.12	110.99	13.06	10.41	20
2	153.97	18.11	1.08	153.60	18.07	3.56	20
3	181.84	21.39	1.43	173.12	20.37	4.25	20
4	182.54	21.47	1.45	171.60	20.19	3.08	20
5	159.72	18.79	1.25	154.42	18.17	2.73	20
6	242.95	28.58	1.84	193.12	22.72	3.32	20
7	505.18	59.43	1.58	465.09	54.72	2.95	20
8	437.10	51.42	1.57	409.26	48.15	3.26	20
9	409.85	48.22	1.92	369.71	43.50	3.44	20
10	326.81	38.45	1.62	281.96	33.17	2.99	20

Fig. 5 is a graphical plot representing the dependence of the tensile stress on the proportional deformation for the group C of tested specimens. Fig. 6 illustrates the test specimens torn in tensile tests.

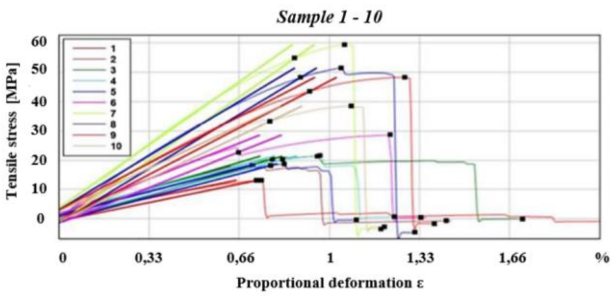

Figure 5. Graphical dependence of tensile stress on proportional deformation - Group C test specimens

Figure 6. Torn test specimens of Group C

4 MATERIALS´ TENSILE TEST EVALUATION

The evaluation of tensile tests lied in comparing the average measured values of the test specimens' results. A comparison of the results of the test specimens of group A and group B can be seen in Tab. 7 and Tab. 8.

Table 7. Average result values of Group A test specimens - PLA color fiber (commercial material)

Group A Average values	Maximal force [N]	Tensile stress at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]
	855.950	100.700	2.025	9339.649	90.556	4.172

Table 8. Average result values of Group B test specimens - PLA color fiber (experimental material)

Group B Average values	Maximal force [N]	Tensile force at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]
	1336.950	161.418	1.986	1454.940	148.883	3.892

From the average values measured in Group A which consisted of 10 PLA test specimens with a color shade (commercial material) the average value of the maximum force measured was 855.95 N. Group B consisted of 10 PLA test specimens with color powder pigment (experimental material). The average value of which was 1336.95 N. The difference between the measured values is 481 N.

This comparison of the results leads us to believe that better performance has shown the test specimens of Group B. Fig. 2 of the group A test specimens after the tensile test shows that the test specimens' layers loosened in the vertical direction which could cause their faster disintegration under a lower loading force. We found that the addition of a blue color pigment in the Group B test specimens not only gave the PLA material a hue, but also increased its strength.

The average test result values measured in the Group C specimens are given in Tab. 9.

Table 9. Average test result values of Group C test specimens - PLA with admixture of glass powder (experimental material)

Group C Average values	Maximal force [N]	Tensile stress at max. force [MPa]	Extension at max. force [mm]	Force at yield strength (Shift 0.2 %) [N]	Tensile stress at the yield strength (Shift 0.2 %) [MPa]	Tensile deformation at failure [%]
	271.220	31.906	1.486	248.287	29.212	3.999

This material under our scrutiny was created to make the material lighter. However, we assumed that making the material lighter would result in degradation of its strength. which was also confirmed in the tensile test. Of the values measured in group C, which consisted of 10 test specimens from the selected PLA with glass powder filler (experimental material), the average value of the maximum force measured was only 271.22 N. The produced material was not compared with other similar material because there are no commercially produced fibers with glass powder admixture. We can consider this material to be experimental only, on which we wanted to prove the possibility of making the material in additive production lighter. In the future, this type of material can be used in applications that do not require much strength, but rather focus on the lower weight of the manufactured products.

5 CONCLUSION

At present, available commercially are different types of fibers of different color, different fiber diameters and different weights. Due to their price, these fibers can also be produced in a home or laboratory environment, which significantly reduces delivery time and financial costs, as their purchase is still a costly investment where it comes to industrial fibers. The development is constantly bringing new research materials in this respect, applicable in various industries, such as the medical industry for the production of prostheses, material produced for the pharmaceutical industry, where various rapidly dissolving materials are used, biogels or nanobiomaterials intended exclusively for additive production [Leary 2020].

In the research presented in this paper polylactic acid (PLA) - based fibers were created primarily for 3D printing technology, with the selected PLA material Ingeo 2003D serving as a building material with experimentally added additives of color powder pigment and glass powder filler. The main goal of the experiment was to create new materials with properties similar to commonly available commercial material. By carrying out the experiment, fibers with different mechanical properties were created under laboratory conditions, which were then compared with commercial materials purchased from a vendor of 3D printing material. The obtained results point to the possibility of using experimentally created fibers directly for the 3D printing process in real laboratory conditions.

ACKNOWLEDGMENTS

Ministry of Education, Science, Research and Sport of SR supported this work within contracts VEGA No. 1/0026/19 and VEGA No. 1/0051/20.

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