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RESEARCH OF THE EFFECT OF FILAMENT HUMIDITY ON THE QUALITY OF 3D PRINTING

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Abstract. This study investigates the process of 3D printing a model with several types of filament at different percentages of material moisture. Due to the unique characteristics of individual plastics, each print requires preliminary setup of both the printer and the printing process, it is also important to prepare the appropriate material. Neglecting at least one of these nuances will lead to an incorrect printing process and, as a result, a deterioration in the quality of the part. The purpose of the study is to determine the value of the percentage of moisture content in the most common types of filament under the condition of high-quality printing, by comparing physical objects printed under different conditions and at different material moisture. An exoskeleton vertebra model was chosen as a test object. The result shows a significant improvement in quality when observing the correct filament moisture requirements and adjusting the printing process accordingly for each plastic.

Keywords: 3D printing, filament, humidity, part quality, 3D printer, exoskeleton vertebra

Introduction

Varieties of 3D printing technologies have been developed with the different function. According to ASTM Standard F2792 [1], ASTM catalogued 3D printing technologies into seven groups, including the binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. There are no debates about which machine or technology function better because each of them has its targeted applications. Nowadays, 3D printing technologies are no longer limited to prototyping usage but are increasingly also being used for making variety of products [2].

Material extrusion-based 3D printing technology can be used to print multi-materials and multi-colour printing of plastics, food or living cells [3]. This process has been widely used and the costs are very low. Moreover, this process can build fully functional parts of product [4]. Fused deposition modelling (FDM) is the first example of a material extrusion system. FDM was developed in early 1990 and this method uses polymer as the main material [5]. FDM builds parts layer-by-layer from the bottom to the top by heating and extruding thermoplastic filament.

The operations of FDM are as follows:

I. Thermoplastic heated to a semi-liquid state and deposits it in ultra-fine beads along the extrusion.

II. Where support or buffering needed, the 3D printer deposits a removable material that acts as scaffolding. For example, FDM uses hard plastic material during the process to produce 3D bone model [6].

3D printing technologies are widely used for the production of polymer components from prototypes to functional structures with difficult geometries. By using fused deposition modelling (FDM), it can form a 3D printed through the deposition of successive layers of extruded thermoplastic filament, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polypropylene (PP) or polyethylene (PE) [7]. Lately, thermoplastics filaments with higher melting temperatures such as PEEK and PMMA can already be used as materials for 3D printing technology [8]. 3D printing polymer materials in liquid state or with low melting point are widely used in 3D printing industry due to their low cost, low weight and processing flexibility [9]. Mostly, the materials of polymers played important role in biomaterials and medical device products often as inert materials, by contributing to the efficient functioning of the devices as well as providing mechanical support in many orthopaedic implants [10].

There are many types of filament with different properties. Below are examples of plastics and their main characteristics that were used for the study:

• PLA – easy to print, biodegradable, variety of colors.

• coPET – more flexible than PLA, not stronger than ABS but devoid of the problem of harmful fumes.

Plastics used in 3D printing have one common and main enemy – humidity. You can easily find countless stories on the net about the filament deteriorating when stored in air. Or examples of unsu-ccessful products printed from such filaments.

It is important to note that some filaments are more susceptible to humidity than others. For example, PLA plastic, PVA support material, nylon and ABS are particularly sensitive to humidity.

Plastics are sensitive to humidity because they are made of materials that easily absorb water or have a high level of hygroscopicity, to put it correctly. For example, PLA plastic is biodegradable and is made from natural resources such as corn or rice. While this is much better for the environment than other plastics, it also means that under certain conditions it will break down into carbon dioxide, water and methane. Humid conditions and UV light accelerate the breakdown of this material. It won't crumble, of course, but it will become unusable. When moisture is absorbed by the filament and then this material is heated by a 3D printer for extrusion, the water combines with the heat to form steam. Naturally, this leads to the formation of bubbles as the filament exits the nozzle and leaves a porous and uneven surface.

Objectives and Problems of Research

Oven. The most common option at home, where you can dry the thread. But you should only use ovens that have controlled heating and temperature regulation, since too high a temperature leads to partial softening of the monofilament and its sticking together. It is also worth turning on the convection function and leaving a gap, without closing the oven completely, for the intake of dry air and the exit of moist air. The biggest advantage is accessibility. Disadvantages: inaccuracy – difficult to achieve precise temperature control; high risk of filament damage due to overheating; need to constantly monitor the drying process.

Vegetable dryer. Food dehydrators are designed to slowly remove excess moisture by providing low heat. The advantage of using a dehydrator is that all you have to do is set the temperature and leave the coil inside to dry. The disadvantage of this drying option is the fact that this equipment is designed to dry materials that have a high moisture content (50–70 %), and in the case of plastics, this figure is lower.

The advantage is that it provides fairly precise control of temperature and humidity. The main disadvantage is the limited capacity, and the dehydrator also needs modernization and is not very common.

A monofilament dryer is a piece of equipment specifically designed to remove excess moisture from filament. The principle behind it is quite simple: they hold a spool of monofilament in a heated housing, which causes the water molecules to evaporate. The simplest monofilament dryers consist of a heated container that fits at least one spool of monofilament. More sophisticated machines are equipped with additional features such as rotation and directional airflow to evenly distribute the heat. In addition, some monofilament dryers are designed to dry the entire spool of monofilament at once, which can then be removed and loaded into a 3D printer. Others are designed to dry the monofilament and feed it into the 3D printer at the same time, which saves time.

It has many advantages over other methods: it provides precise control of temperature and drying time, which is critical for many types of filament; most dryers have automatic programs for different types of materials, which simplifies the process; it is also safe, protected from overheating and has safety systems. The only disadvantage is the cost, because it is the most expensive option among all methods.

Using vacuum bags will allow you to maintain the moisture state of the plastic for a long time. They differ from regular ziplock bags in that they have a hole where you can connect a vacuum cleaner and suck out all the air. No air = no moisture or other elements that degrade the quality of the thread! To use your material, you need to take it out, and close it again when you are finished. By the way, you can make the bag even more effective by adding a few packets of silica gel to it! These are small packets of moisture-absorbing gel that you have definitely seen in shoe boxes. An alternative to vacuum bags can be airtight boxes or containers, and it can be anything from food containers to large buckets that you can find in any hardware store. If you follow these rules, the filament will be stored for a long time without losing its properties.

Example of drying time and temperature of different polymers is given in Table 1.

Table 1

Drying time and temperature of different polymers

Filament Type	Optimal drying temperature, °C	Minimum drying time, hours	Additional recommendations
PLA	40–45	4–6	Most common, not very hygroscopic. Suitable for beginners
coPET	50–55	6–8	More flexible than PLA, strong, not stronger than ABS but devoid of the problem of harmful fumes
ABS	80–85	6–8	Prone to warping at high temperatures. Requires an enclosed chamber
PETG	70–80	4–6	Good bed adhesion, chemical resistant
TPU	60–70	4–6	Flexible, requires a well-calibrated extruder
Nylon	80–90	8–10	Strong, abrasion resistant, but hygroscopic
ASA	80–85	4–6	UV resistant, good weatherability
PC	100–110	8–10	Strong, heat resistant, but requires high print temperatures
HIPS	80–85	6–8	Soluble in D-limonene, used for support structures
PLA+	40–45	4–6	Improved PLA with higher strength and impact resistance
PET	80–90	6–8	Strong, rigid, chemical resistant
TPU95A	60–70	4–6	Very flexible, used for elastic parts

It is worth remembering that for plastics such as Nylon, Elastan, the option of drying at 40 °C does not work, but for twice as long. These plastics do not dry in such conditions!

These data are relative, as they can fluctuate depending on how wet the filament is, especially when it comes to drying time.

These articles are useful and help to better understand how to handle plastic, but the advice on drying cannot be called accurate and following them does not always lead to the desired result. Determining specific indicators will allow you to better control the printing process and help achieve maximum 3D printing quality.

Main Material Presentation

Preparation. The study consists of three stages for each plastic. The stage has three steps, namely: taking measurements; printing a test model; fixing the result, preparing the filament for the next stage.

Each subsequent stage should improve the quality of the printed object. Printing will be performed with two types of filament PLA and coPET. Before starting work, you need to make sure that the plastic used has a sufficiently high percentage of moisture for taking measurements, if not, then ensure that the quality of the thread "deteriorates".

Preparation of a 3D model that will be used as a test model. For this, a vertebra model for an exoskeleton was chosen (Fig. 1). The selected model consists of various shapes, such as a sphere, a truncated cube and various types of rounding, which is very good for a test model, and the presence of which will help to better understand the quality of the printed object.

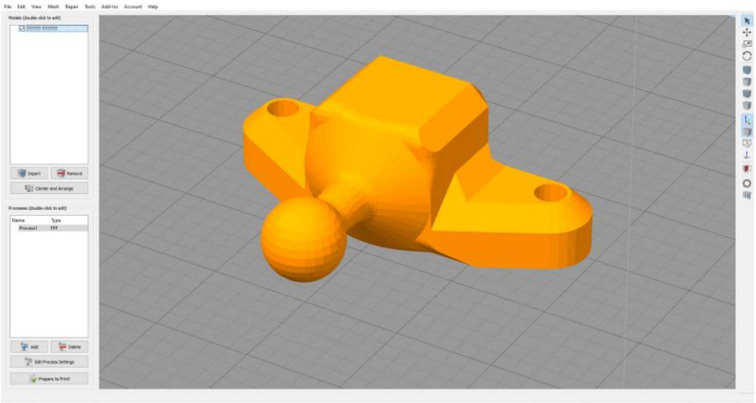


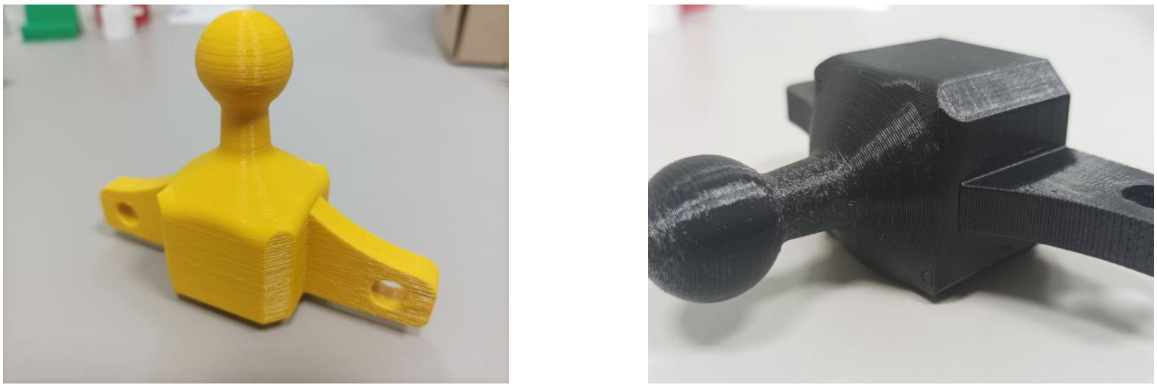
Fig. 1. Model in Simplify 3D environment

Preparing the environment and setting the printing parameters. To generate gcode from the stl format, the Simplify 3D slicer program was used (Fig. 1, 2). The main printing parameters: generating supports; model filling 25 %; table temperature 70°C and 50°C for coPET and PLA, respectively; nozzle temperature 235 °C and 220 °C for coPET and PLA, respectively; also when printing PLA, maximum air was used.

Stage 1. A hygrometer was used in conjunction with a vacuum pump to measure the filament humidity. The measurement of humidity in the filament was carried out as follows: the plastic with the hygrometer was sealed, it was decided to leave the package for some time to stabilize the device's indicators. After this time, the values were fixed and the "measured" filament was sent for printing. Different colors of plastic were used when printing, but the manufacturer and type of plastic did not change, so we can say that this did not affect the research.

coPET. The spool was stored in the wrong conditions for about 4 months, namely not packed in a sealed bag. It was decided to start working with it. The initial measurement showed 61 % humidity.

During printing, a slight crackling sound was heard, this is the process of moisture evaporation from the filament, as a result of which characteristic bubbles appeared on the model.



a b

Fig. 2. The part is printed on coPET, humidity 61 % (a); the part is printed in PLA, humidity 60 % (b)

After completing the printing (Fig. 2) and analyzing the result, we can conclude that at a humidity of 61 %, the object turned out to be of poor quality. You can see the unevenness of the layers, it seems that the printer is not calibrated. But this is just the result of the formation of bubbles during extrusion.

PLA. Since at the beginning of the research, the PLA plastic spools were stored in compliance with the requirements, their first use fell, as it turned out later, on stage 2. After that, the filament was placed in a humid room and was there for two weeks. As a result, the initial measurement was 60 % humidity.

As with coPET printing, a characteristic crackling appeared. After removing from the table, various bumps and funnels are visible over the entire area of the part, this is the result of moisture evaporation from the filament. It is worth noting that the humidity indicator is not much different from coPET, but the part looks better, this is due to the fact that although the hygroscopicity indicator of PLA is high, it does not have such a negative impact as in other types of plastics. Also, there is another indicator of filament humidity on the object – filament stretching (Fig. 2), in simple words, threads appear at the end of a layer and the transition to the next one.

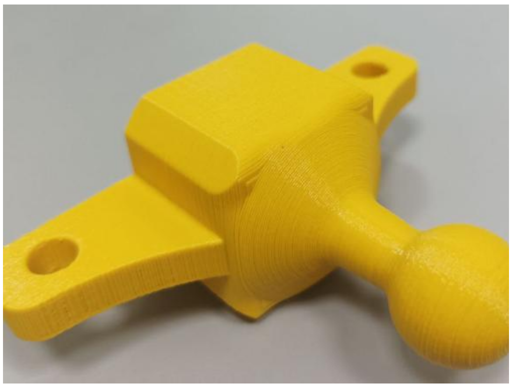
It is also worth mentioning that when printing with coPET filament, the printer was forced to stop due to a blockage inside the nozzle. This is precisely the result of printing with a polymer with excessive moisture.

After printing, the spool with the filament was disconnected and sent for drying. A food dehydrator was used for drying. This choice is due to the fact that, at the time of the study, there was no special dryer for the filament. Since the drying temperature of the studied plastics is not high, the use of an oven was impractical.

The coPET spool was dried at a temperature of 59–60 °C for 4 and a half hours.

PLA plastic was dried for 4 hours and 30 minutes at a temperature of 42 °C.

Stage 2. Repeated measurements showed that the moisture content in coPET is 40 %, in PLA – 44 %.



a

b

Fig. 3. The part is printed on coPET, humidity 40 % (a); the part is printed in PLA, humidity 44 % (b)

The object printed with coPET plastic (Fig. 3, *a*) shows that changing the moisture content by 21 % for the better gave a positive result. When enlarged, the presence of layer displacement is visible, but not as strong as it was at the 1st stage. In general, the print quality improved.

At this stage, the test model was modernized, namely, the shape of the processes (wings) of the vertebra changed. This helped to avoid the use of supports in some places, and as a result, reduce the consumption of printing material.

When changing the PLA moisture content from 60 % to 44 %, the print quality improved, but funnels and bumps can still be seen on the parts (Fig. 3, *b*). At the correct angle of incidence of light on a white object, the bumps leave a shadow and it becomes easier to notice them (Fig. 3). It is worth noting that the quality of printing of the outer rounded shapes has increased, but the inner plane has almost not changed in quality. There are also thin threads, which indicate the tension of the thread, as in the previous stage.

After fixing the results, the plastic must be dried again. The technology remains the same, first the dehydrator is heated to the desired temperature, the coil is placed in the dehydrator box. The indicators are checked every 20 minutes to prevent them from changing by more than 1 unit.

The coPET coil was in the middle of drying for 3 hours, the temperature indicator was 60 °C. PLA plastic was dried for 3 hours at a temperature of 41–42 °C.

Stage 3. As a result of the extreme measurements, we have the following figures: the moisture content in coPET is 27 % and in PLA – 33 %.

During the printing process, there were no more obvious signs that the filament contains a large amount of moisture, namely, when laying layers, the formation of balls that would form when water evaporates from the filament during the extrusion process was not noticed. Also, the material did not crack and no unnecessary tension appeared.

Having analyzed the coPET object (Fig. 4), we can say that the print quality has significantly improved. All previous defects have disappeared, the layers have become uniform and identical in appearance, and the surface of the part has become smoother. On the plane of the part, traces of the end of the layer remained, when the extruder remains in place for some time and the molten plastic continues to flow through the nozzle. These traces will remain on the object, since this is how the 3D printer works.

a b

Fig. 4. The part is printed on coPET, humidity – 27 % (a); the part is printed in PLA, humidity – 33 % (b)

After printing with PLA filament and analyzing the resulting part, it is possible to note an improvement in the quality of the printed part (Fig. 4, *a*)). Defects in the form of funnels, pits and bumps are not observed on the plane of the object. The absence of tension and a significant improvement in the quality of the internal area also indicate excellent print quality (Fig. 4, *b*)).

Results and Discussion

So, in the images you can see a clear difference in the quality of the parts. Before starting work, the printer was calibrated, and the printing parameters for a single filament did not change throughout the study. This suggests that the quality of the printing process and the quality of the printed object directly depended on the state of the polymer, namely on its humidity. Fig. 5 shows the assessment of print quality and details depending on the moisture content of the filament.

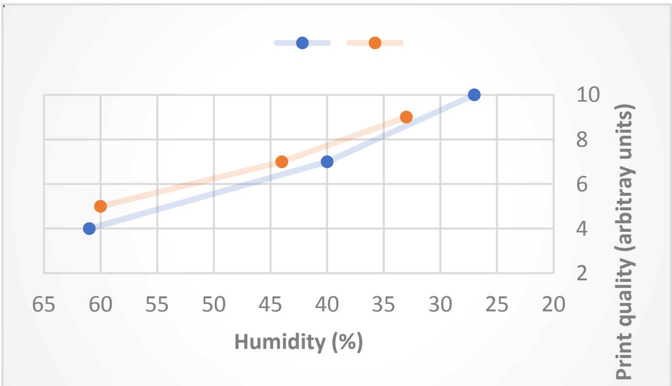


Fig. 5. Assessment of print quality

The graph shows that humidity has a greater effect on coPET, while in the case of PLA the difference in quality is noticeable but has a smaller effect.

To assess the print quality, the following parameters were taken into account: surface roughness, presence of thread tension, number of defects (bubbles, bulges on small-area elements) per plane in percent, adhesion of the part to the table, and printing of overhanging elements (bridges).

Drying was done using a food dehydrator, which entailed a number of nuances. This method of drying requires constant monitoring of the indicators and their correction as needed. Almost every such dehydrator requires a design change for the need to dry plastic. Such changes can be irreversible, so it is worth carefully considering such actions if the device is not intended to be used for such tasks constantly.

The filament coil can be dried directly using a 3D printer, or rather a heated bed. To do this, you need to place the coil on the printing work area and set the bed heating parameter. However, this method has many disadvantages. The heat is concentrated directly above the bed, which means the filament will not heat up evenly, from the bottom up. This may not be suitable for printers with a small work area, without a bed heating function and plain open printers. But while the drying process is in progress, printing cannot take place, and vice versa. This is the biggest drawback of this method.

The total drying time of each coil is 7 hours 30 minutes, and the percentage of moisture evaporation per unit of time was determined by calculations:

$$x = \frac{t_2 * (y_1 - y_2)}{t_1} \quad (1)$$

where x – percentage of moisture evaporation per unit, %; y_1 – moisture content before drying, %; y_2 – moisture content after drying, %; t_1 – drying time, min; t_2 – desired calculation time (1 hour), min.

The value for coPET filament is 4.6 % for the first drying and 4.3 % for the second.

And for PLA plastic the values are as follows: 3.5 for the first drying and 3.6 for the second.

As a result, it turns out that in 1 hour of drying, a coPET type polymer at a temperature of 60 °C loses 4.5 % of moisture, and a PLA polymer loses 3.5 % of moisture at a temperature of 60 °C. temperature of 42 °C.

Fig. 6 shows in the form of a graphical dependence how the % humidity of the filaments changed in relation to the drying time.

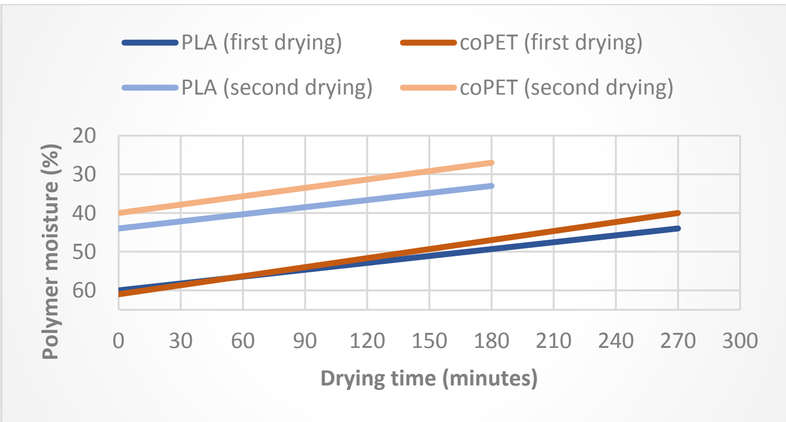


Fig. 6. Plastic drying out over time

As can be seen, the coPET polymer is better able to dry and generally shows better quality results. However, as the moisture content increases, the quality drops significantly. PLA polymer dries less intensively, but is generally more loyal to the humidity parameter.

The printing process depends on many factors, one of which is the quality of the polymer with which printing is carried out. If during the preliminary extrusion of part of the filament from the nozzle bubbles appear on the material and a slight crackling sound is heard, you should not start printing. This is one of the most visible consequences of the moisture of the thread. Further use of such a filament will not only manifest itself in reduced quality of printed objects, but will most likely lead to nozzle clogging. And as a result of cleaning and repairing the device.

Conclusions

The study included printing a test model with several types of polymer with different percentages of moisture content for each. The value of this variable was monitored and fixed, provided that the highest print quality was achieved and, as a result, the maximum quality of the printed object was achieved. This helped to assess the quality based on several parameters. Calculations were also made that show how the moisture value changes over time during drying.

On the basis of this, the corresponding graphs were created.

The result demonstrates a significant improvement in quality when observing the correct requirements for filament moisture and adjusting the printing process accordingly for each plastic.

Added recommendations for drying reels on the printer table; this method is relatively the most affordable and does not require equipment preparation in most cases, although it has a number of disadvantages.

Nowadays, 3D modeling and 3D printing occupy a large niche in the field of manufacturing various parts and objects. A very common technology is FDM, it is used both in home use and by larger organizations. Printers with FDM technology use a polymer in the form of a thread that is wound on a spool, the printing process is performed by fusing one layer onto another.

There are many types of filament on the market, each has its own properties and is used in different areas, for individual tasks. It is important to store the filament correctly so that it does not change its properties or lose them. The filament must be dried so that excess moisture does not affect the quality of the print. The principle of drying is the same for all types of plastic, but the methods for each are different.

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ДОСЛІДЖЕННЯ ВПЛИВУ ВОЛОГОСТІ НИТКИ НА ЯКІСТЬ 3D ДРУКУ

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Анотація. У статті досліджено процес 3D-друку моделі з кількома типами ниток за різних відсотків вологості матеріалу. Через унікальні характеристики окремих пластиків кожен відбиток потребує попереднього налаштування як принтера, так і процесу друку, також важливо підготувати відповідний матеріал. Нехтування хоча б одним із цих нюансів призведе до некоректного друку і, як наслідок, до погіршення якості деталі. Мета дослідження – на основі порівняння фізичних об’єктів, надрукованих у різних умовах та за різної вологості матеріалу, визначити значення відсотка вмісту вологи в найпоширеніших видах філамента за умови високоякісного друку. Тест-об’єктом вибрано модель екзоскелета хребця. Результат засвідчив істотне покращення якості у разі дотримання правильних вимог щодо вологості нитки та відповідного регулювання процесу друку для кожного пластику.

Ключові слова: 3D-друк, нитка, вологість, якість деталей, 3D-принтер, екзоскелет хребця.