FORWARD AM
Innovating Additive Manufacturing

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Influence of Moisture on Filaments for FFF 3D Printing

Filament moisture on Ultrafuse® PET CF15: Aesthetics, Mechanical Properties, and Best Practices

Contents

1.0 Abstract

In Additive Manufacturing (AM), the increasing demand for thermoplastic filaments that meet industrial needs has led to a continuous improvement and higher material standards. Considering plastic filaments, the criteria include color, diameter, ovality, filament moisture level, etc. The moisture level of a filament is a result of the hygroscopic behavior of the material. The water molecules in the filament may cause issues in both the printer and printed part, aside from the filament itself. One of the most undervalued problems in the whole process is the filament moisture uptake while printing. The following white paper provides an overview of the importance of moisture in thermoplastic filaments, specifically in Ultrafuse® PET CF15. Additionally, the paper documents the negative impact on aesthetics, the influence of moisture on dimensional accuracy and the decrease of mechanical properties. State-of-the-art solutions are proposed to maintain a controlled (high) temperature and low moisture surrounding environment for the spools and respective filaments.

2.0 Introduction

Moisture is the presence of water in small amounts in the form of vapor within a solid. Moisture absorption is the ability of a material to absorb the vapor from the surrounding environment. In the context of Fused Filament Fabrication (FFF), the material is plastic filament. Common to many other extrusion techniques such as injection molding, the quality and properties of a raw material such as pellets may affect the final material filament [1]. Moisture absorption may be due to free water liquid/vapor which collects in pores and voids or is absorbed and connects to hydrogen bonds within the material structure resulting in swelling [3]. The diffusion of water particles into the polymeric material may change material properties such as glass transition and viscoelastic behavior [3].

Although the drying process is common in other traditional manufacturing techniques, there is still little research done on the impact of moisture in Additive Manufacturing throughout the various material categories.

The filament moisture level a customer receives when opening a spool of plastic filament is the result of the moisture absorbed during production, packaging, shipping, storage, and environmental conditions. From the pellet to the final printing process, the material goes through several environments and changes which may lead to a decrease in quality. Non-conditioned rooms from the production site to the printing location increase the odds of irregularities in the filament moisture content within a spool resulting in inconsistencies in the print process.

Different levels of moisture may result in different mechanics, questioning the repeatability of the manufacturing process itself. Repeatability and high mechanical properties for 3D printing are becoming not only a desire but also a requirement for material manufacturers. Users are demanding better filament quality with high mechanical properties to bridge the usage of Additive Manufacturing from prototyping to final parts. Engineering grade polymers are specially designed to fulfill these engineering and design constraints.

BASF Forward AM offers a wide array of filaments, from standard materials including Polylactic Acid (PLA), Acrylonitrile butadiene styrene (ABS), and Polypropylene (PP) to advanced engineering materials such as Carbon Fiber Polyethylene Terephthalate (PET CF15), High temperature Polyamide (PAHT), Thermoplastic Polyurethane (TPU), Polyamide (PA), Polyphenylsulfone (PPSU). While many plastics have an overall tendency to pick up moisture, the moisture does not have the same impact on every material. In AM, certain filaments have a higher tendency to absorb water than others, making them more susceptible to a decrease in not only physical characteristics but also in mechanical properties due to the presence of water molecules. Within Forward AM's portfolio specifically, it is estimated that the material classes of butene-diol vinyl alcohol copolymer (BVOH), polyamides, thermoplastic polyurethanes and polyethylene terephthalates have a higher hygroscopic behavior.

PET CF15 is polyethylene terephthalate filled with 15% of carbon fibers. The material is used in frames, prototyping, drones, facemasks, etc. The fibers in the matrix allow for more strength and stiffness while still maintaining low weight. Although the material is filled with 15% carbon fibers, PET CF15 offers a matte finish, avoiding the need for postprocessing when taking aesthetics into consideration. PET in its natural form is already susceptible to moisture uptake that may be increased with the reinforcement of fibers [5]. Although carbon fibers are more hygroscopic than glass fibers, it is also important to consider the compatibility between the matrix and the fiber chosen [5]. Figure 1 presents the filament moisture level of Ultrafuse® PET CF15 in a conditioned room with ~23°C °C and average relative humidity of ~33%.

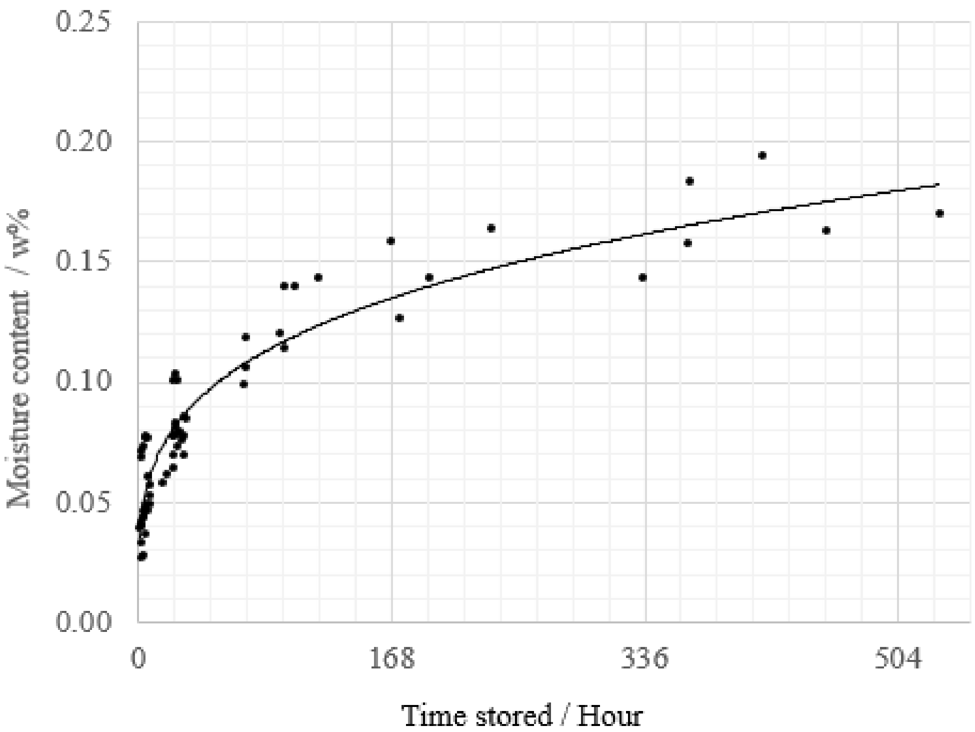

Figure 1: Absorption behavior of PET CF15 at ~23 °C and average relative humidity of 33 %

The trend is dependent on both environment moisture and temperature. Under different circumstances (humid environmental conditions), the equilibrium point will be higher as will the rate of filament moisture uptake. A reliable repeatability print process is dependent on the filament moisture content of both filament and the environment where it is used.

3.0 Impact of Filament Moisture on Printability

The increase of moisture in the filament can have various effects on the overall printability of the material. Some of the issues seen in moist parts are bubbles formed due to the increase in vapor pressure in the hot end. An increase of oozing and stringing may be resultant from the decrease in viscosity due to the water molecules. The filament moisture once evaporated will also create voids decreasing the overall weight of the part along with increasing the dimensions. The change in viscosity will also affect the extrusion flow and print quality. Figure 2 illustrates a printed part utilizing Ultrafuse® PET CF 15 with a filament moisture content of 0.17 w%.

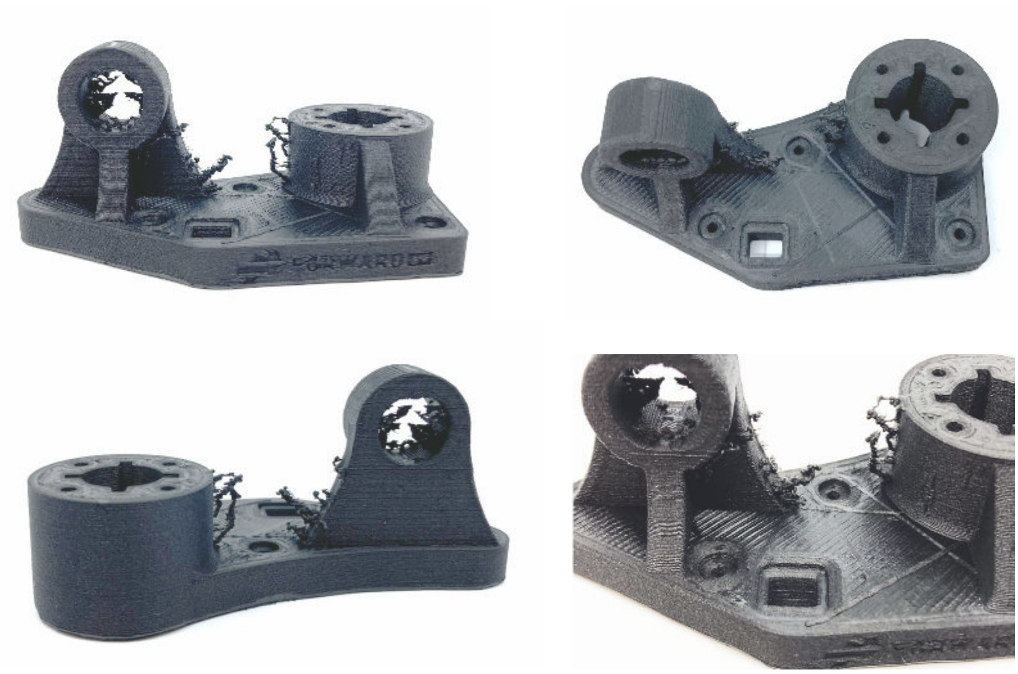

Figure 2. Printed part with filament moisture content of ≥ 0.17 CV w% [7].

The variation in flow due to filament moisture creates an extrusion surplus that is deposited while printing once the nozzle can no longer hold the material. The nozzle can also pick up the over extruded material when moving within the part resulting in poor aesthetics, both in flat surfaces and small ones. Intricate details and parts that require high retractions also show poor quality due to the oozing and stringing. Although the results can be improved, the parameters will only hold within a certain range of filament moisture content as the material continues to change in relation to the increase in filament moisture. The excess material may be removed by hand, but with high filament moisture content parts may only be taken with tools. In a continuous and repetitive process, reprinting the same part with the same G-code using a moist spool followed by a new spool that may be dryer will likely result in under extrusion.

Figure 3 presents the same part with a lower filament moisture content of ≥0.007 w% and respective optimization.

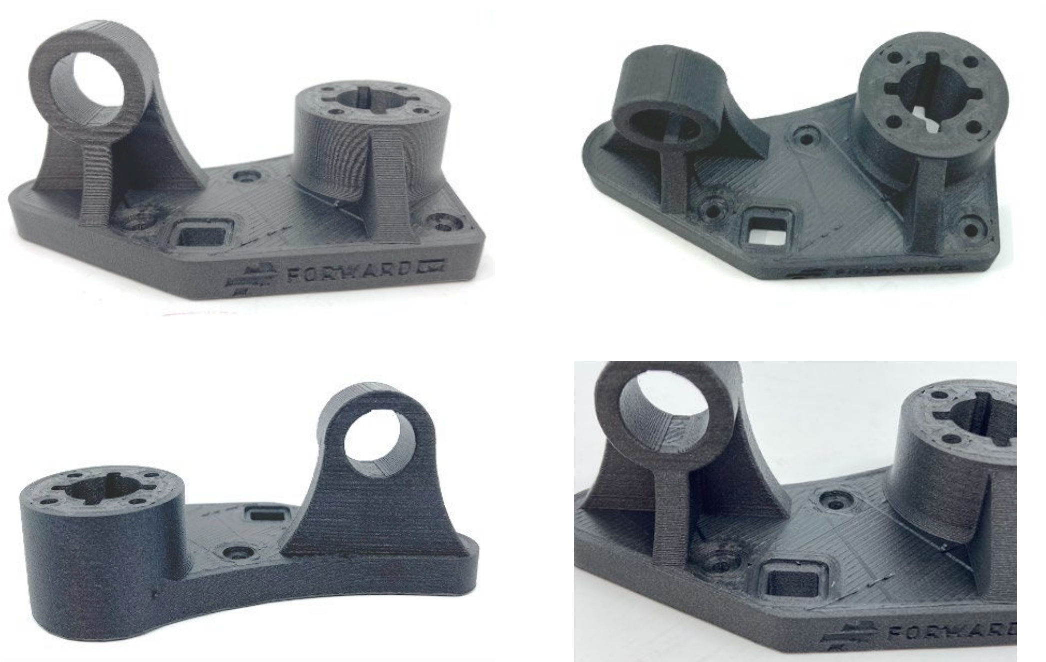

Figure 3. Printed object where the used filament had a moisture content of ≥0.07 w%.

An overall decrease in aesthetics may be seen in filament moisture content above 0.07 w%. These effects are further visible in lighter colours and more moisture-sensitive filament materials.

4.0 Impact of Filament Moisture on Dimensional Accuracy and Part Properties

The impact of filament moisture is further seen in changes in weight and dimensions when considering the physical properties of an object. The evaporation of trapped water from the filament material during extrusion results in an overall decrease in weight due to foaming and bubbles. Figure 4 presents the change in weight of Ultrafuse® PET CF15 over 8-10 days when printed in different surrounding environments. Bars (4mmx10mmx80mm) were printed under standard environment conditions of 22.4 – 23.2 °C and a mean relative humidity of 33.1 – 33.4 % or humid conditions of ~23 °C and a mean relative humidity of ~70%.

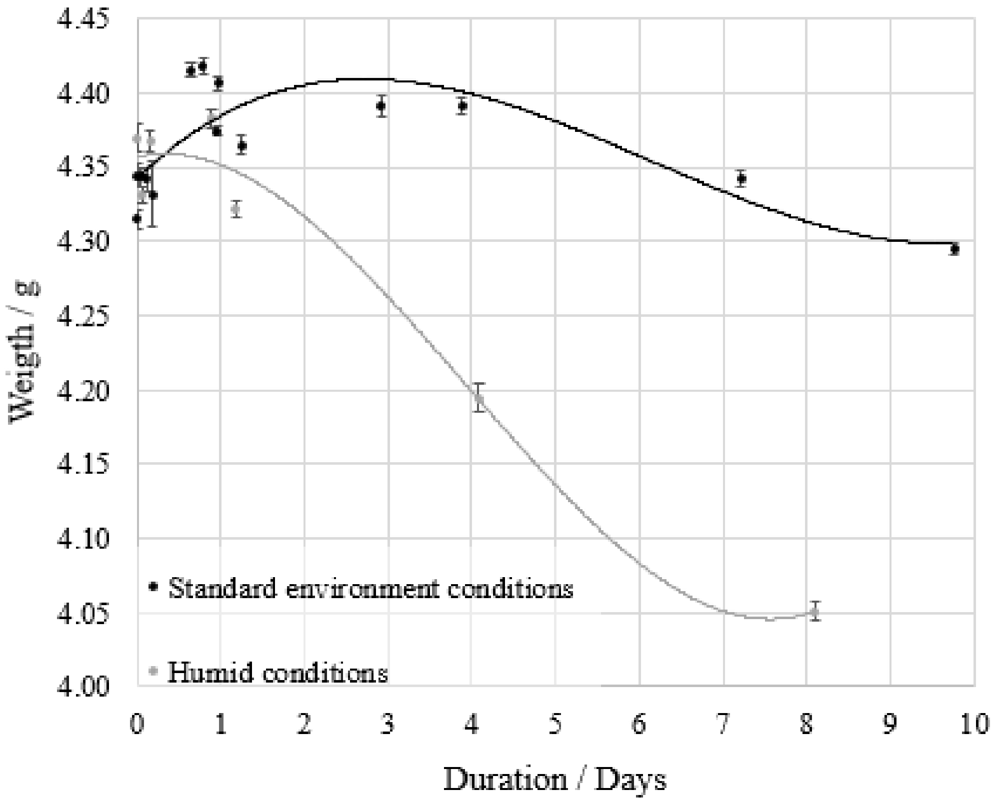

Figure 4: Part weight changes per average over storage time of Ultrafuse® PET CF15 filament

Overall, the weight tends to decrease over time with a higher impact on humid conditions.

Regarding dimensions, the neck width of tensile bars type 1A were measured with different filament moisture levels to assess the impact of filament moisture in dimensional accuracy as shown in Figure 5. The filament spool was initially dried in a vacuum oven at 60 °C for at least 60 hours

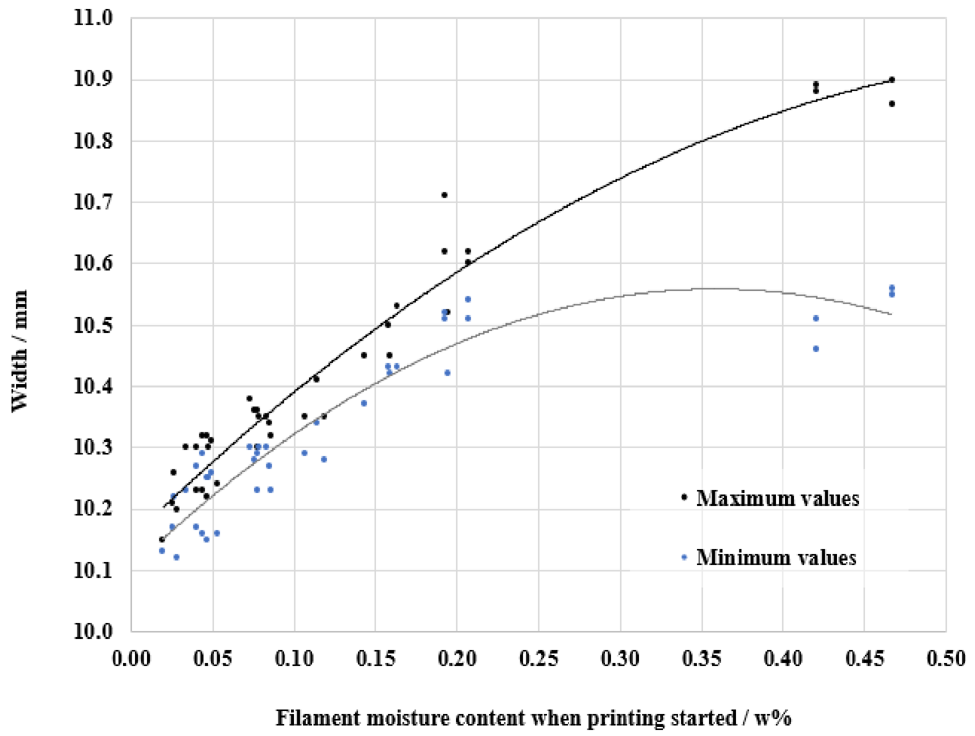

Figure 5: Effects of filament moisture on printed tensile bars' edge width

According to the graph, the dimensions of the parts have a tendency to increase with moisture content in the filament. In addition, the discrepancy between the maximum and minimum value increases suggest that the surface becomes rougher and more irregular with the increase of filament moisture.

The difference in aesthetics and dimensions will also impact the mechanical properties. To assess the impact of filament moisture in mechanical properties several tensile bars type 1A were printed in the XY direction with different filament moisture levels. The tensile bars were tested according to ISO 527. The print settings are available in Appendix A. Figure 6 presents the tensile curves under different filament moisture contents.

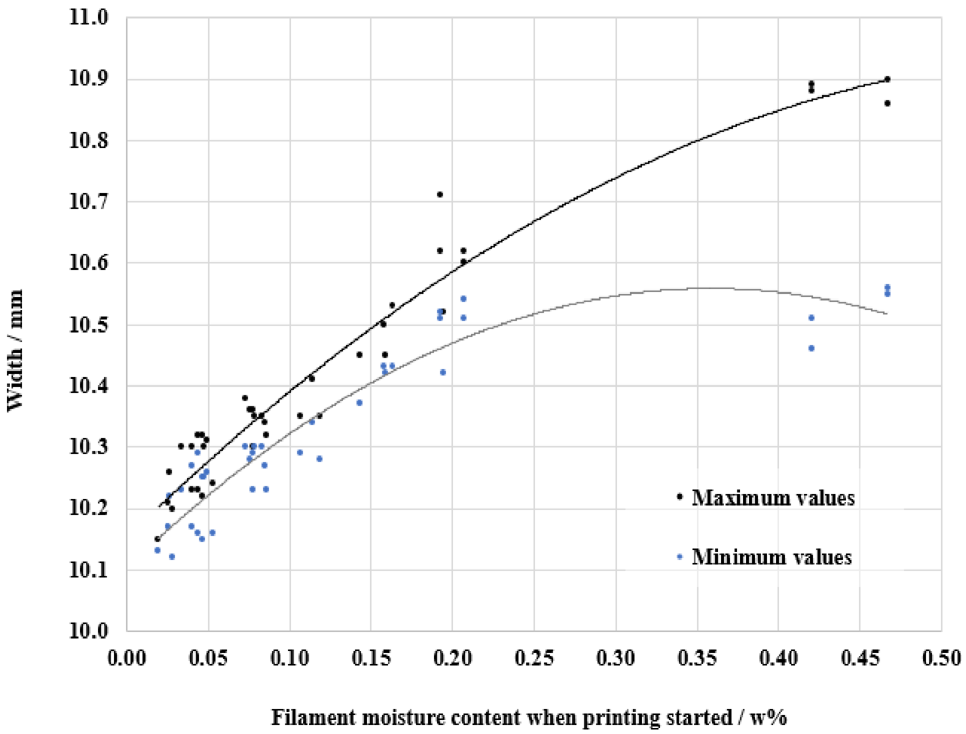

Figure 6: Stress-strain curves of the printed PET CF tensile bars when printed with a different filament moisture content, labels indicate moisture content in weight percentage (w%).

Overall, the increase of filament moisture content tends to decrease the tensile properties. With a filament moisture content between 0.15-0.2 w%, the mechanical properties tend to decrease by 10 - 15% when printing Ultrafuse® PET CF 15. Additionally, when printing objects with a filament moisture content of 0.4 - 0.5 w% the decrease in tensile strength tends to be approximately 24%. The presence of voids decreases layer adhesion which suggests that there will also be a decrease in strength in any printed direction.

5.0 Reducing Filament Moisture

Several stakeholders within the 3D Printing ecosystem have tackled the filament moisture impact from different angles. Engineers and industrial users see filament moisture as a concern in particular for engineering applications where dimensional accuracy or high mechanical properties are essential for a smoother shift from injection molding to additive manufacturing. To successfully print parts with accuracy and consistency, a primary concern should be environmental conditions. By keeping the surrounding moisture level low and constant, the filament in turn may also maintain a low moisture content for a longer period of time. This is imperative, especially for small series production where repeatability is needed to meet standards and consistency. State of the art drying equipment includes:

5.1 Airtight Boxes

Airtight boxes allow for a consistent moisture environment when fully sealed. It is also advised to add desiccant to keep the environmental moisture content low. The sealing is the most important step, given that there is no heat to continuously dry the material. This solution is not permanent, but increases the reliable printability time window. Any air opening will have an impact on the rate of absorptance specially in highly humid environments. Figure 7 presents the results regarding Ultrafuse® PET CF15 when keeping the box fully enclosed and when keeping an open tube through it which is usually necessary during 3d printing.

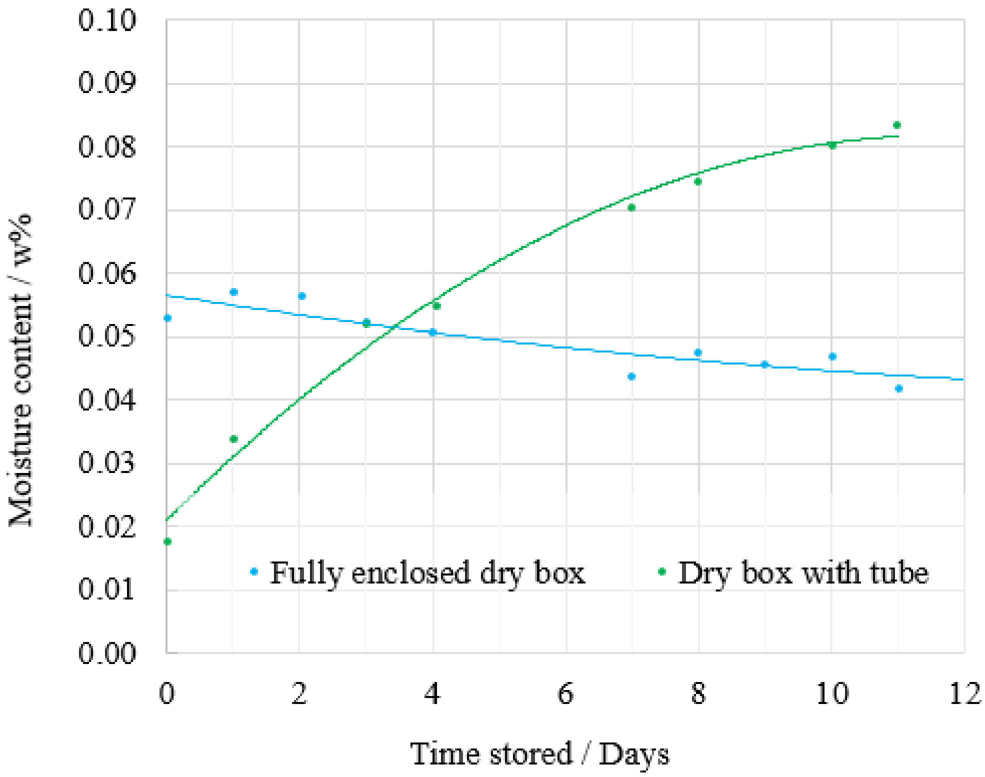

Figure 7. Filament moisture content (w%) of Ultrafuse® PET CF while stored in a dry box

5.2 Actively Heated Dry Cabinet

An Actively Heated Dry Cabinet offers the right conditions for storage and even drying over a longer amount of time (days). This solution is usually not connected to the printer. Continuous storage in a dry cabinet with low moisture will also maintain certain materials at low moisture levels. Active drying is preferred over an enclosed box as the air will be above room temperature. Figure 8 presents the results regarding Ultrafuse® PET CF15 while kept at 30 °C and 0% environment moisture.

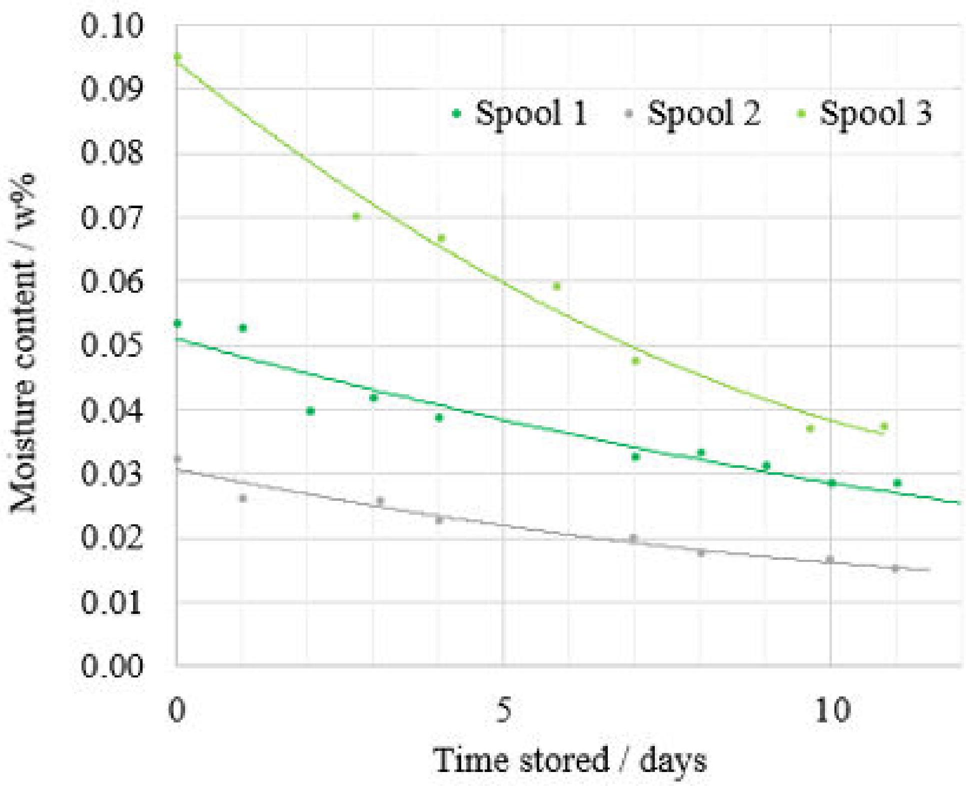

Figure 8. Filament moisture content (w%) of PET CF while stored in the dry cabinet at 30 °C and 0% relative humidity;

5.3 Actively Heated Dry Storage Box

An Actively Heated Dry Storage Box (such as Daywise) have been able to provide a solution independent of spool size to dry the material while printing. The continuous drying process while printing allows for longer successful prints connecting the moist filament to a dry and consistent filament extrusion therefore increasing print process repeatability.

5.4 Hot Air Dryer

A Hot Air Dryer is able to remove moisture from hygroscopic filaments by blowing hot air and dissipating the moisture into the surrounding air [6]. Materials such as PET or TPU present good results when used with a hot air drying oven. Figure 9 shows the results when drying Ultrafuse® PET CF15 at 60 °C during 32 h.

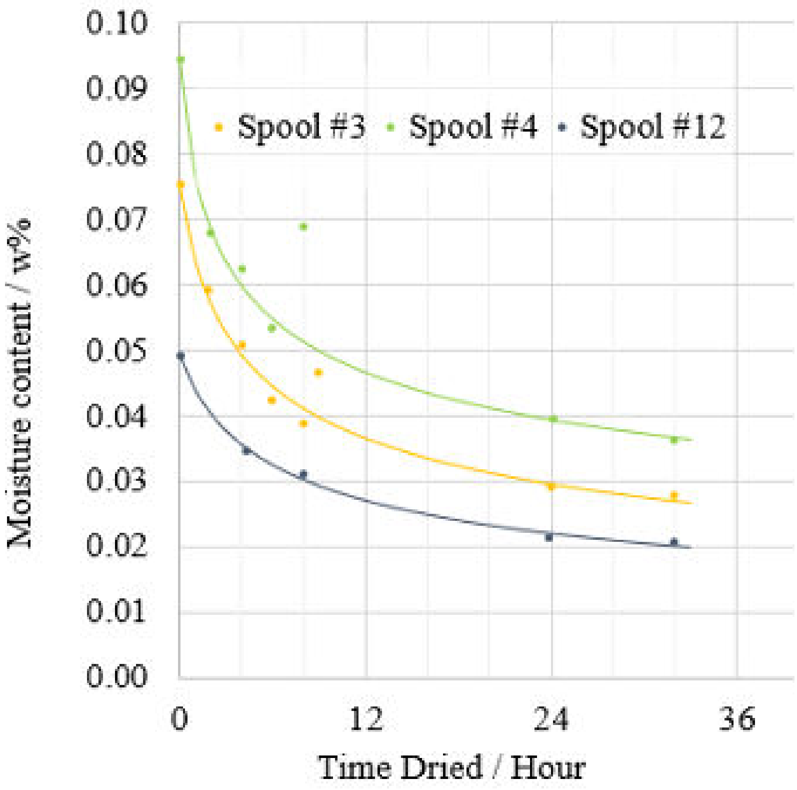

Figure 9: Filament moisture content of PET CF filament in the Hot Air dryer at 60 °C

5.5 Vacuum Oven

The low pressure in a vacuum oven not only allows for a faster decrease in air moisture with the removal of free moisture, but also reduces bound moisture within the solid [4]. The vacuum significantly decreases the boiling point of water [6]. If the product is heat sensitive, the vacuum oven temperature may also be reduced resulting in lower energy consumption and less degradation of the material [4]. A vacuum oven is specifically recommended when drying PA and PPSU filaments. Figure 10 shows the results when drying Ultrafuse® PET CF15 at 60 °C during 40-48 h.

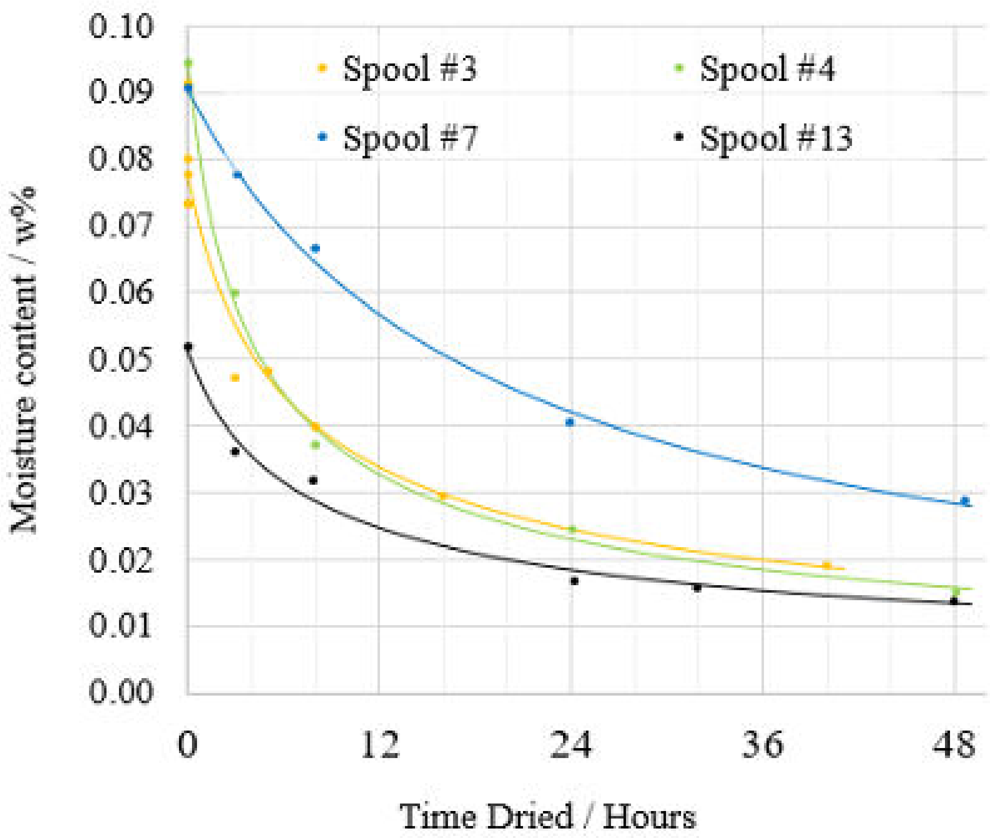

Figure 10: Moisture content of PET CF filament during drying study dried in the vacuum oven at 60 °C and 15 mBar pressure

The choice between all the available solutions provided will depend on the application and material performance needed. Their success depends on:

- Being fully sealed
- Having some active heating
- Having extremely low relative humidity/low moisture (as low as 1% if possible)

Features with limited capabilities are not suitable for the final solution and the continued reliability of the filament in a continuous production setup. Suppliers that may offer active drying or AM machine manufacturers with integrated low humidity chambers should always be checked for the three key points mentioned above. Checking the humidity within the chamber is also important in order to store the material for a longer amount of time. Storage options with limited humidity control or storing the filament in any non-sealed environment, such as a holder inside or outside the printer or a separate non-sealed filament storage, will not provide an airtight seal and will pick up moisture.

Additionally, reinforced and flexible materials present the biggest challenge when a setup has an extended distance between the extruder and the spool. Flexible materials will tend to stretch and change diameter which may impact the extrusion flow. Reinforced materials also have a tendency to break due to their brittleness. Long and curvy paths may be too difficult for the filament to go through leading to the ideal case scenario of a tube from the material storage unit feeding directly into the extruder.

6.0 Conclusion

Filament moisture has a vast impact in the overall success of additive manufacturing. The absorbance and retention of water from the environment can greatly influence the aesthetics, dimensional accuracy and mechanical properties of hygroscopic materials. The presence of moisture can be evaluated quantitatively for more accuracy, nonetheless it can also be assessed qualitatively at high filament moisture contents. For the continuous success and reliability, it is always advised to maintain polymer filaments at constant low moisture levels. Ultrafuse® PET CF15 is not advisable to print above 0.7 w% when aiming for top level aesthetics and mechanical properties. State of the art solutions including ovens and airtight boxes may increase successful printing processes for a smoother adoption of 3D Printing in production facilities.

7.0 Appendix

7.1 Printer Information & Settings

- Model: 216931 Ultimaker® S3 (EU)
- Serial No: BPP-021557-068456
- Ultimaker® Cura software version: 4.11.0
- Build plate made of glass and sprayed twice with 3DLAC™ Adhesive spray before every print. Test specimens were all printed in XY direction ond by one.

Table 15. Slicer settings used for printing test specimens

Slicer Setting	Value
Material	BASF Forward AM Generic Ultrafuse® PET CF15
Print core	CC 0.6
Quality	
Layer Height	0.2 mm
Initial Layer Height	0.4 mm
Line Width	0.6 mm
Initial Layer Line Width	100.0 %
Walls	
Wall Line Count	2
Z Seam Alignment	User Specified
Z Seam X	0.0 mm
Z Seam Y	0.0 mm
Top/Bottom	
Top Layers	0 (automatic)
Bottom Layers	999999 (automatic)
Top/Bottom Pattern	Zig Zag
Extra Skin Wall Count	0
Infill	
Infill Density	100.0%

Slicer Setting	Value
Infill Pattern	Zig Zag
Material	
(Initial/Final) Printing Temperature	260.0 °C
Build Plate Temperature (Initial Layer)	75.0 °C
Flow	117.0 %
Initial Layer Flow	100.0 %
Speed	
Print Speed (All parameters)	40 mm/s
Initial Layer Speed	16.0 mm/s
Travel	
Retraction Distance	6.5 mm
Retraction Speed	25.0 mm/s
Combing Mode	Within Infill
Layer Start X	0.0 mm
Layer Start Y	0.0 mm
Cooling	
(Maximum) Fan Speed	0.0 %
Support	
Generate Support	Disabled
Build Plate Adhesion	
Build Plate Adhesion Type	Skirt
Skirt Line Count	2
Skirt Distance	5.0 mm

7.2 References

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