Identification of the Sensitivity of FDM Technology to Material Moisture with a Fast Test

Adam Hamrol, Maciej Cugier, and Filip Osiński(✉)

Faculty of Mechanical Engineering, Poznan University of Technology, Poznan, Poland
filip.osinski@put.poznan.pl

Abstract. The growing popularity of the Fused Deposition Modeling method in the industry and among individual users motivates to constantly research its potential. In particular, the influence of the moisture of the material on the result of the process has not yet been sufficiently described. The article presents a test that allows to determine this effect in an experiment requiring a relatively small number of repetitions. As a case study, a test for identifying the effects of material temperature, ply thickness, extrusion rate and material flow on dimensional accuracy, tensile strength and surface quality was presented. As a result of the conducted research, the possibility of using the method with a constant change of factors in the development of parameters of additive manufacturing was confirmed. In the tests performed, a significant increase in the dimensions of the produced samples was also noted with the filament moisture content at the level of 0.74%. For the given humidity, a significant deterioration of the visual condition of the surface was also noted. The moisture of material does not significantly affect the mechanical strength of the samples.

Keywords: Fused Deposition Modeling · FDM · Filament moisture · Design of experiments

1 Introduction

Materials used in Fused Deposition Modeling (FDM) are mostly polymers characterized by significant hygroscopicity. When stored, such a material absorbs moisture from its surroundings and water molecules are attached to polymer molecules, forming an intermolecular bond. Such a connection may cause microcracks that weaken polymer fibers and form empty spaces between layers. This phenomenon creates problems in polymer processing and in the quality of manufactured parts, for example in [1–5]:

- extruder jamming - water absorbed in the filament evaporates while melting in the heater block, which may result in material supply interruption
- deterioration of mechanical properties of product (material strength)
- large discrepancies in dimensions
- defects and high surface roughness

M. Diering et al. (Eds.): MANUFACTURING 2022, LNME, pp. 156–165, 2022.
https://doi.org/10.1007/978-3-031-03925-6_14

Material used for FDM processing is delivered in the form of a wire and is commonly referred to as filament. One of the most common filaments is made of a polymer known as ABS. The recommended moisture of this material is 0.2–0.3% [6, 7]. To reduce moisture absorption, it is recommended to store ABS filament in special containers. If the moisture is too high, the filament should be dried. The recommended drying time and drying temperature depend on the type of material properties. For ABS, they are on average about 6 h and 80 °C [8, 9].

The effect of filament moisture on the properties of FDM products depends to a large extent on the printing conditions, primarily on the type of printing device [10]. Therefore, it is reasonable to develop an easy, cheap and fast test to determine how significant this effect is and how much it depends on FDM parameters, such as filament temperature, layer thickness, and filament speed. This information can be viewed as a kind of process diagnostics [11] and should be helpful for an operator when setting the process parameters of the stability of the filament moisture is uncertain.

2 The Test Methodology

The test presented in this paper is based on an experiment with a systematic change of process parameters (*P*) [12]. These parameters are referred to as "factors" in the terminology of design of experiments [13]. The advantage of this type of experiment is the small number of trials needed to obtain reliable data on the influence of a large number of factors (i.e. four or more) on the results of the process. Its weakness is the lack of information on the interaction between factors, which can be identified, for example, in a factorial experiment. However, for the purpose of the presented test, these interactions are irrelevant. Such a limitation means that the test can be used mainly in the case of basic materials (filaments) that are used in additive manufacturing with the FDM method. Thanks to the application of the presented test, the operator can make an unambiguous decision regarding the modification of the process parameters or putting the filament for drying in order to obtain the required print parameters.

For each factor, two levels of its setting are determined:

– level (+) - giving potentially better process results (Y_B)
– level (−) - giving potentially worse process results (Y_W)

In the first part of the experiment, two trials are carried out:

1. with all factors on the level " + " (All (+))
2. with all factors on the level "−" (All (−))

Two statistics are calculated:

– the difference of average values obtained in the trials:

$$D = \overline{Y_B} - \overline{Y_W}$$

– the average range of results in each of the trials:

$$\overline{R} = \frac{R_B + R_W}{2}$$

If the ratio:

$$q = \frac{D}{\overline{\overline{R}}} > q_c$$

it can be concluded that the difference (D) of averages $\overline{Y_W}$ and $\overline{Y_B}$ is a result of the process parameter settings. The value of q_c is adopted as the critical value of a test for averages difference in t-Student distribution.

Based on the value of $\bar{R}$ and for the given significance level α, upper and lower limits of confidence interval (UCL and LCL) of $\overline{Y_W}$ and $\overline{Y_B}$. are calculated.

In the second part of the experiment, two series of trials are carried out:

1. with all factors set on (+) but with one factor P_i set on (−)
2. with all factors set on (−) but with one factor P_i set on (+)

If the value Y in a trial is located outside the confidence interval of $\overline{Y_W}$ and $\overline{Y_B}$, it can be concluded that the influence of this factor on process outcomes is important.

The number of trials necessary to carry out the experiment is $n = 2k + 2$, where k is the number of process parameters investigated. Each trial should be replicated at least 3 times. For example, this means that $k = 3$, the number of trials is 8, and the number of all replications 18.

The test is carried out in the following steps:

1. Preparation of at least two sets of filaments – one of the moisture recommended by the manufacturer, and the other with a maximum moisture expected in the conditions in which it is stored.
2. Selection of properties important for the manufactured product.
3. Selection of process parameters that have significant impact on the product properties selected.
4. Scheduling the plan of the experiment.
5. Conducting a set of the planned experiment trials.
6. Calculation of the average values confidence intervals.
7. Analysis of the obtained results.

3 Case Study

3.1 Tested Object

The tests were carried out on a Zortrax M200 Plus additive manufacturing 3D printer. Samples of a standardized shape intended for mechanical tests PN-EN ISO 527-2:2012 were printed [8] (Fig. 1).

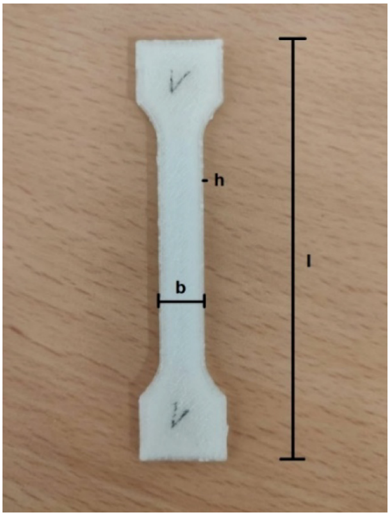

Fig. 1. Sample shape and dimensions.

The model of the sample for printing was designed in Autodesk Inventor, exported to.zprojx format, and launched in Z-SUIT, which allowed for the preparation of executive files for the Zortrax device.

The moisture content of the material for printing was tested on a RADWAG MA 50/1.R moisture analyzer.

3.2 Product and Process Parameters

The following properties of the sample were measured:

– sample width - *B* [mm].
– R_m tensile strength [MPa]
– appearance of the surface (visual evaluation); three states of surface quality were distinguished:

1. good
2. acceptable
3. nonacceptable

The sample width (*B*) was measured by electronic caliper Mitutoyo 500-181-30, with a measuring accuracy to ±0.01.

A statistical stretch test was carried out on a SunPoc WDW-5D-HS device according to the procedure described in EN ISO-527 [8, 9].

A Delta Optical Smart 5MP Pro microscope was used to assess the quality of the surface structure.

Four process parameters were adopted as experiment factors:

- *P1* - material temperature during extrusion
- *P2* - the thickness of the applied material layer
- *P3* - extrusion speed - nozzle moving speed, that extrudes the plastic relative to the table
- *P4* - material flow - amount of molten polymer flowing through the nozzle in the unit

Based on the results of previous tests [1] and literature data, the levels (+) and (−) of factors (i.e. process parameters) were defined (Table 1) at which the sample proper-ties should presumably be better (Y_B) or worse (Y_W).

Table 1. Parameter (i.e. factors) and levels of their setting.

Mark	Parameter type	(+)	(−)
P1	Material temperature	245 °C	255 °C
P2	Layer thickness	0.09 mm	0.39 mm
P3	Extrusion speed	27 mm/s (0%)	30 mm/s (10%)
P4	Filament flow	0%	10%

The ABS filament was tested in three humidity states: 0.25%, 0.34% and 0.75%.

3.3 Plan of the Experiment

The plan of the experiment is presented in Table 2.

Table 2. Plan of the experiment.t

Factor	No. of trial	Level	No. of trial	Level
All factors (+)	1a	All (+)	1b	All (−)
Hotend temperature	2a	*P1 (−) All (+)*	2b	*P1 (+) All (−)*
Layer thickness	3a	*P2 (−) All (+)*	3b	*P2 (+) All (−)*
Extrusion speed	4a	*P3 (−) All (+)*	4b	*P3 (+) All (−)*
Filament speed	5a	*P4 (−) All (+)*	5b	*P4 (+) All (−)*

The experiment was carried out according to the plan in Table 2. Three replications were performed in each trial.

3.4 Presentation of Results and Calculations

The results of the experiment in regard to the width, strength and surface quality of the sample are summarized in Table 3.

Table 3. Results of the experiment.

No. of trial	Factor level		Width - B [mm]			Strength R_m [MPa]			Surface quality 1, 2 or 3		
			Filament moisture								
			0.25%	*0.32%*	*0.74%*	*0.25%*	*0.32%*	*0.74%*	*0.25%*	*0.32%*	*0.74%*
1	a	All (+)	10.07	9.96	10.07	32.91	28.04	30.26	1	1	2
	b	All (−)	10.27	10.31	10.51	24.19	23.89	21.08	2	2	3
2	a	P1 (−) All (+)	10.06	10.04	10.12	31.6	32.29	29.22	1	2	2
	b	P1 (+) All (−)	10.27	10.28	10.38	23.83	23.97	21.57	1	2	2
3	a	P2 (−) All (+)	10.23	10.17	10.26	17.38	17.22	17.98	1	2	3
	b	P2 (+) All (−)	10.23	10.26	10.29	32.73	33.55	31.71	1	2	2
4	a	P3 (−) All (+)	10.01	10.02	10.11	30.24	28.12	30.36	1	2	3
	b	P3 (+) All (−)	10.26	10.28	10.44	24.43	22.33	20.67	1	1	2
5	A	P4 (−) All (+)	10.17	10.26	10.25	28.73	30.52	32.61	2	3	3
	b	P4 (+) All (−)	10.16	10.19	10.34	16.96	18.00	18.65	1	2	2

The results of the significance tests of the ratio q and limits of confidence intervals regarding the average values of width and strength of the sample are presented in Tables 4 and 5.

Table 4. Significance tests and confidence intervals for width

Moisture		Y	R	$\bar{R}$	D	q	$q_{kr} = 0.89$	*UCL*	*LCL*
							α = 0.05; Student's t-distribution		
0.25%	All (+)	10.07	0.08	0.080	0.2	2.5	Significant	10.20	9.94
	All (−)	10.27	0.08					10.40	10.14
0.34%	All (+)	9.96	0.07	0.075	0.35	4.67	Significant	10.08	9.84
	All (−)	10.31	0.08					10.43	10.19
0.74%	All (+)	10.07	0.06	0.055	0.44	7.33	Significant	10.16	9.98
	All (−)	10.51	0.05					10.60	10.42

Table 5. Significance tests and confidence intervals for strength

Moisture		Y	R	$\bar{R}$	D	q	$q_{kr} = 0.89$	*UCL*	*LCL*
							α = 0.05; Student's t-distribution		
0.25%	All (+)	32.91	0.61	0.480	8.72	18.16	Significant	33.67	32.15
	All (−)	24.19	0.35					24.95	23.43
0.34%	All (+)	28.04	1.28	1.480	4.15	3.29	Significant	30.40	25.68
	All (−)	23.89	1.68					26.25	21.53
0.74%	All (+)	30.27	3.0	2.350	9.18	3.91	Significant	34.01	26.53
	All (−)	21.09	1.7					24.83	17.35

In order to facilitate the analysis of the results obtained they are presented graphically in Figs. 2 (a–d), 3 (a–d) and 4.

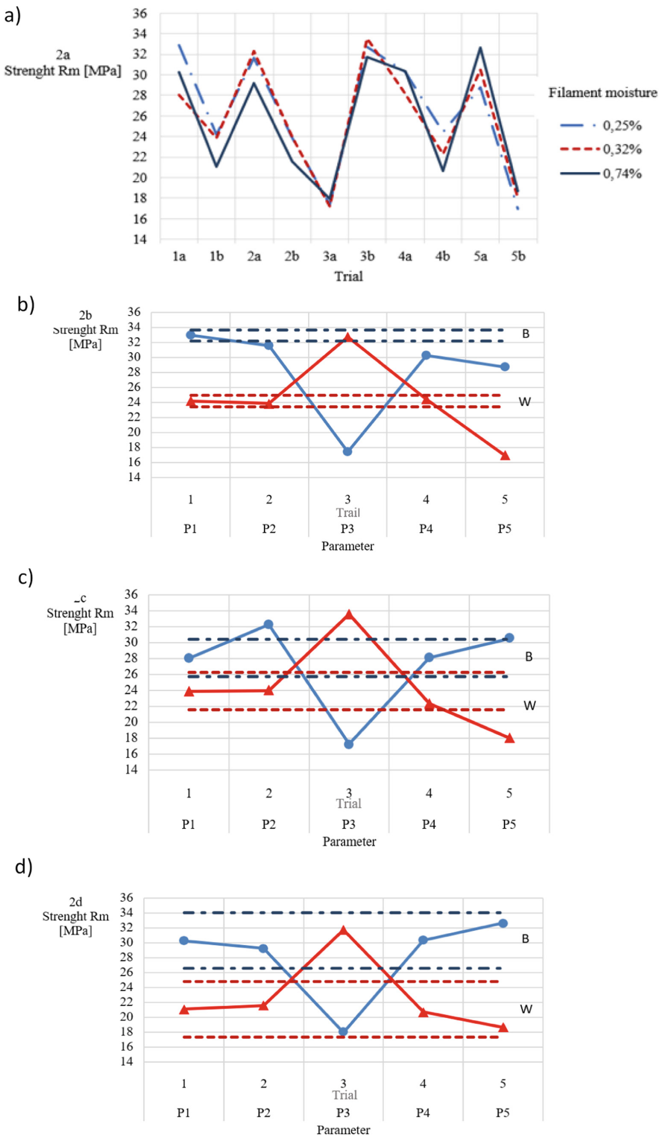

Fig. 2. Sample strength depending on the level of factors for different filament humidity

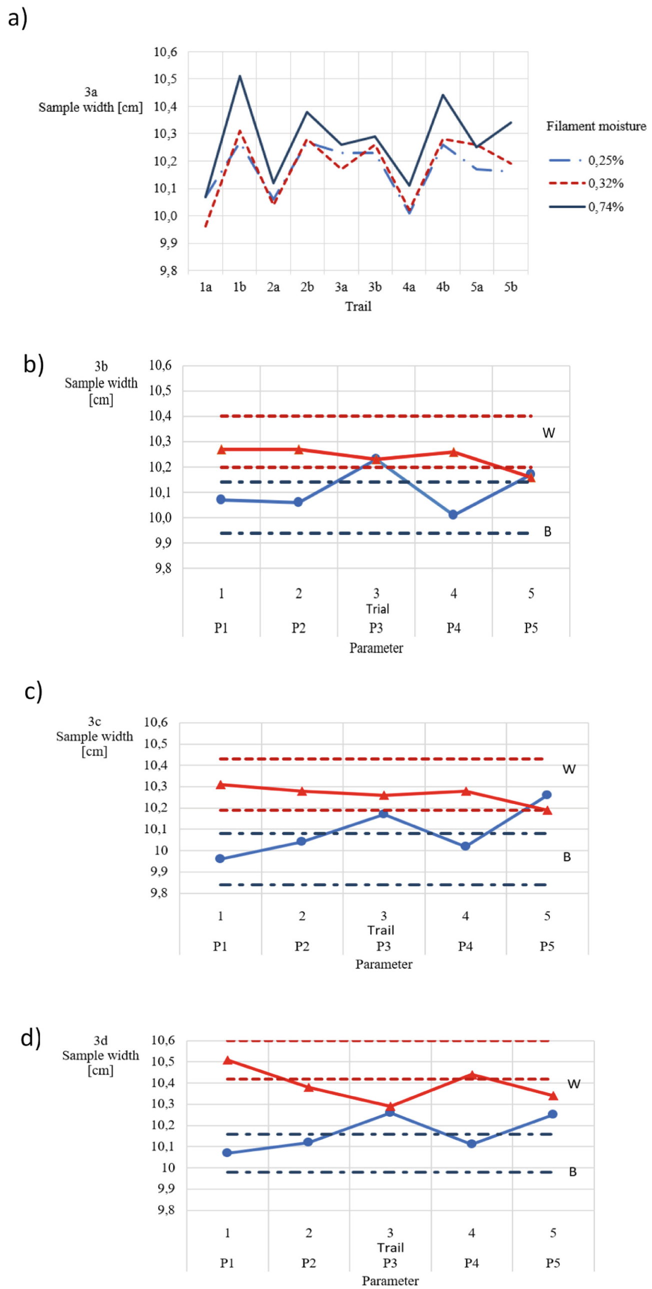

Fig. 3. Sample width depending on the level of factors for different filament humidity.

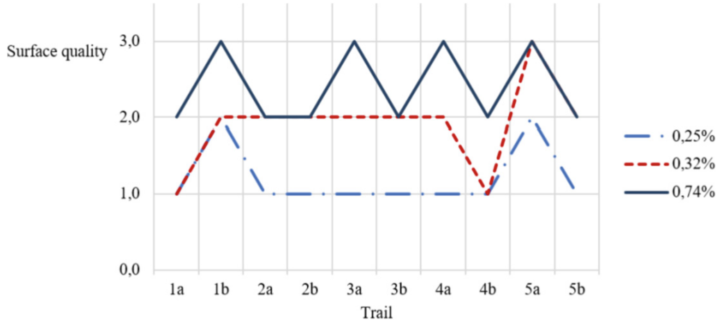

Fig. 4. Surface quality depending on the level of factors for different filament humidity.

4 Analysis of the Results

The results of the experiment can be used as a basis to decide about the need to dry filament, or to give guidance on parameter settings that allow you to reduce the negative impact of filament moisture on the printing results.

Material moisture had a significant impact on the dimensional accuracy of the samples. With an increase in filament moisture, the width of a sample increases, thus the difference between the actual dimension and the nominal dimension increases. However, the differences at moisture levels of 0.25% and 0.34% are quite irrelevant. A strong increase in the sample width for the 0.74% moisture level was measured. The dimensional accuracy of the sample affects the thickness of the layer and the speed of the filament supply.

The moisture of material does not significantly affect the mechanical strength of the samples. However, as with the width of a sample, the sample strength is affected by the layer thickness and filament flow speed – the highest strength is achieved at the parameters setting All (+) and P2 (+) All (−).

A deterioration of surface quality for samples printed with filament with 0.74% moisture is noticeable. The individual material paths and surface damage are more visible, which can be directly translated into a greater surface roughness.

The final decision on the need to dry filament depends on the process operator or the customer that needs the manufactured products. In this case study, it would be reasonable to dry the filament in cases where the dimensional accuracy and the surface quality of the product are crucial.

In addition, in a case of suspected high humidity of filament, and in the absence of proper preparation of material for production (i.e. drying), it is recommended to adjust the process using the material speed. Increasing this parameter, while maintaining a constant flow, causes in practice a reduction of the amount of material. It can be presumed that a similar effect can be obtained by decreasing the flow of filament through the nozzle, but in the above example, such a case was not analyzed.

References

1. Wichniarek, R., Hamrol, A., Kuczko, W., Górski, F., Rogalewicz, M.: ABS filament moisture compensation possibilities in the FDM process. CIRP J. Manuf. Sci. Technol. **35**, 550–555 (2021)
2. https://vshaper.com/pl/blog-pl/jak-wilgoc-wplywa-na-wlokno-drukarskie-3d/. Accessed 04 Aug 2021
3. Algarni, M.: The influence of raster angle and moisture content on the mechanical proper-ties of PLA parts produced by fused deposition modeling. Polymers **13**, 237 (2021). https://doi.org/10.3390/polym13020237(2020)
4. Cueto, C.I.A.: Anisotropy and humidity effect on tensile properties and electrical volume resistivity of fused deposition modeled acrylonitrile butadiene styrene composites. PUCP (2017)
5. https://blog.gotopac.com/2018/03/01/how-3d-printer-filament-storage-cabinets-instantly-improve-3d-print-part-quality/#Whats_Wrong_with_Drying_3D_Printer_Filament_by_Baking_It. Accessed 04 Aug 2021
6. https://filament2print.com/gb/blog/45_humidity-problems-3d-filaments.html. Accessed 04 Aug 2021
7. Broniewski, T., Kapko, J., Płaczek, W., Thomalla, J.: Test methods and evaluation of the properties of plastics. Wydawnictwo Naukowo-Techniczne, Warszawa (2000)
8. Standard Syntetics: Determination of mechanical properties at static stretching. PN-EN ISO 527-2:2012
9. Standard, Determination of mechanical properties at static stretching. PN-EN ISO 527–1:2012
10. Galeja, M., Hejna, A., Kosmela, P., Kulawik, A.: Static and dynamic mechanical properties of 3D printed ABS as a function of raster angle. PMCID: PMC7013835 (2020)
11. Hamrol, A.: Process diagnostic as a means of improving the efficiency of quality control. Prod. Plann. Control. **11**, 8 (2000)
12. Bhote, K.R.: Qualitaet – der Weg zur Weltspitze. IQM – Institut fuer Qualitaetsmanagement, Grossbottwar (1990)
13. Montgomery, D.C., Runger, G.C.: Applied Statistics and Probability for Engineers, 6th edn. Wiley, New York (2014)