1. Robert Grolik[1], 2. Michał Góra[2], 3. Mateusz Góra[3], 4. Mateusz Dyląg[4]

AGH University of Science and Technology in Krakow, Department of Manufacturing Systems, Faculty of Mechanical Engineering and Robotics (1)(2), Cracow University of Technology, Department of Materials Science, Faculty of Material Engineering and Physics (3)(4)
ORCID: 1. 0000-0001-8382-0490, 2. 0000-0001-8680-5675, 3. 0000-0002-0028-5312, 4. 0000-0002-6916-4228

doi:10.15199/48.2021.11.23

A study of the influence of external factors on the temperature control process of a 3D printer head in FDM technology

Streszczenie. *Celem badań przedstawionych w artykule jest zbadanie wpływu mierzalnych parametrów zewnętrznych oraz nie-wprost mierzalnych zakłóceń na ilość oddawanej przez głowicę drukarki energii cieplnej. W badaniach uwzględniony został wpływ temperatury wewnątrz komory drukarki i temperatury uplastyczniania materiału w głowicy na ilość zużywanej energii elektrycznej przy regulacji temperatury algorytmem PID o parametrach zapewniających wartość błędu regulacji poniżej 3°C. W podsumowaniu przedstawiono uogólniony poziom wpływu poszczególnych parametrów, co daje wyraźne wskazówki, które z nich należy uwzględnić oraz opomiarować podczas budowy pełnych regulatorów temperatury dla drukarek 3D (dot. projektu nr POIR.01.01.01-00-2064/15).* ***(Badanie wpływu czynników zewnętrznych na proces regulacji temperatury głowicy drukarki 3D w technologii FDM)***

Abstract. *The aim of the research presented in this article is to examine the influence of measurable external parameters and non-directly measurable disturbances on the amount of thermal energy emitted by the printer head. The research took into account the influence of the temperature inside the printer chamber and the plasticizing temperature of the material in the head on the amount of electricity consumed when controlling the temperature with the PID algorithm with parameters ensuring the value of the control error below 3°C. The summary presents a generalized level of influence of individual parameters, which gives clear indications which of them should be taken into account and measured during the construction of complex temperature regulators for 3D printers (concerns project no. POIR.01.01.01-00-2064/15).*

Słowa kluczowe: Wytwarzanie addytywne, Druk 3D, Technologia FDM, Regulacja temperatury
Keywords: Additive manufacturing, 3D printing, FDM technology, Temperature regulation

Introduction

3D printing in FDM technology [1] (Fused Deposition Modeling) or otherwise called FFF (Fused Filament Fabrication) is one of the Rapid Prototyping methods - it is intended to produce parts of production quality in a relatively small number, if desired, at a relatively low cost, taking into account the cost of unit production of other manufacturing techniques [2]. However, the continuous development of this technology and its increasing popularity implies more and more attempts to use 3D printing in FDM technology for production applications where requirements for the product are precise and it is not possible to apply "concessions" which can be used in the case of prototyping. The key parameter influencing the overall quality, combining both visual (visible defects, artifacts) and technical features (strength, roughness) is the temperature in the printing head – a place where the material is heated and transitioned from solid to liquid phase.

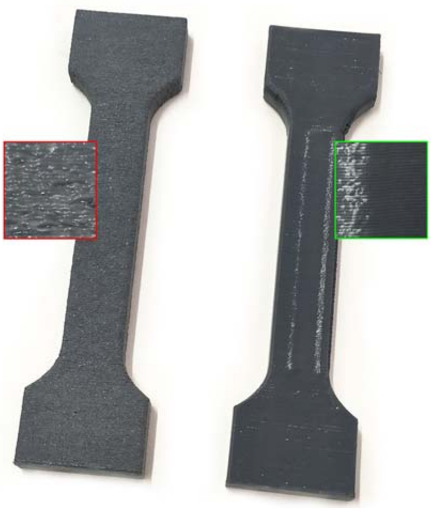

Fig. 1. Comparison of printouts produced in different temperature conditions

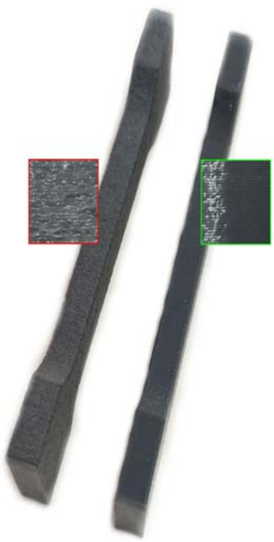

Fig. 2. Comparison of printouts produced in different temperature conditions

Currently, in FDM printers, the temperature control mainly uses classic PID or bang-bang algorithms, which are most effective in stationary systems, to which the 3D printer head does not belong due to the multitude of measurable and non-directly measurable factors affecting the reception of thermal energy from the heating block. The aim of this article is to present results of the study of their influence on the amount of thermal energy consumed by the printer head during the PID algorithm control. The developed conclusions from these studies are significant in the context of working on algorithms improving the quality of temperature control in the head, and thus the above-described print quality.

The photos below (Fig. 1, Fig. 2) show an exemplary printout in two variants: produced in the correct temperature conditions (in the photos on the right) and defective due to incorrect temperature in the printer head during operation (in the photos on the left).

Research assumptions

a) Models were selected and a G-Code was prepared for subsequent main tests - temperature course measurements:

-Overview of the models in terms of ranges of material flow speed through the head for various types of printers (desktop and industrial standard). The process of determining the histogram of these values will consist of the analysis of 4,324,800 lines of code for selected models printed on standard size 3D printer - ATMAT Signal device and 2,346,800 lines of code for models printed in new technology for big volume 3D printers. The test will consist of extruding a certain amount of material at random speed through the generated sequence (a sequence of movements with random displacement and random speed, values will be generated so that their histogram is consistent with the Gaussian distribution with the average value and standard deviation obtained when testing the models, assuming that negative flows – retraction - are not taken into account).

-Generating G-Code for both tests: it was assumed to generate a course that allows: extruding 10g of PLA and a volumetric PETG equivalent (which is 3460 [mm] of filament with a diameter of 1,75 [mm]) at random speed with normal distribution with previously obtained parameters μ = 330,2 [mm / min], σ = 137 [mm / min] using the ATMAT Signal printer, and a second course, which will allow extruding of 100g of PLA and the volumetric equivalent of PA6 (which is 13050 [mm] of filament with a diameter of 2,85 [mm]) at random speed with normal distribution with previously obtained parameters μ = 1924,1 [mm / min], σ = 492,9 [mm / min] using the new print head design and control algorithms (referred further as “Research subject”).

b) Defining the course of research:

-determining starting conditions of the process: measurement will start no earlier than 5 minutes after conditions in the printer stabilize,

-choice of materials: 3 materials of the Polymaker brand were selected

Table 1. Material parameters comparison

Material	Min. nozzle temp [°C]	Max. nozzle temp [°C]	Melting temperature
PolyLite™ PLA	190	230	150
PolyMax™ PETG	230	240	no data
Polymaker N600 PA6	280	300	215

-Determination of measurement points and recorded parameters - the following will be recorded: head temperature, theoretical value of material flow based on the extruder drive position, the amount of energy supplied to the head via the heater - 100% efficiency and completely resistive nature of the heaters are assumed. The following measurement points were assumed:

Table 2. Test conditions

Printer	Head temperature [°C]	Table temperature [°C]	Chamber temperature [°C]	Material	Nozzle diameter [mm]
ATMAT Signal	190	30	30	PLA	0,8
ATMAT Signal	210	30	30	PLA	0,8
ATMAT Signal	190	40	40	PLA	0,8
ATMAT Signal	210	40	40	PLA	0,8
ATMAT Signal	220	30	30	PETG	0,8
ATMAT Signal	240	30	30	PETG	0,8
ATMAT Signal	220	40	40	PETG	0,8
ATMAT Signal	240	40	40	PETG	0,8
Research subject	190	30	30	PLA	2,5
Research subject	210	30	30	PLA	2,5
Research subject	190	40	40	PLA	2,5
Research subject	210	40	40	PLA	2,5
Research subject	280	30	30	PA	2,5
Research subject	300	30	30	PA	2,5
Research subject	280	40	40	PA	2,5
Research subject	300	40	40	PA	2,5

-selection of algorithms allowing to reduce the studied courses to interpretable data set. Registering the amount of delivered energy will be done by numerical integration of the heater's power using the Simpson method. The heater power sampling frequency is 10Hz.

c. Preparation of test stands for testing in isolated conditions.

-Adapting the printer drivers to record data needed to conduct tests - continuous recording of previously defined parameters - generating a record with a frequency of 10Hz of the following parameters: heater power (PWM signal value), material flow speed (extruder drive speed), head temperature.

-Measuring and regulating temperature of important printer elements - temperature on the printer table will be maintained by the PID controller controlling a built-in heater, in the printer chamber temperature will be regulated by a thermostat coupled with a duct heater.

-tuning the head PID controller so that the absolute value of temperature deviation in the entire tested operating range does not exceed 3°C.

Results:

Below are presented the energy consumption graphs, divided into 4 graphs of the energy consumption growth during extrusion:

a. PLA through 0.8mm nozzle (fig. 3)
b. PET through 0.8mm nozzle (fig. 4)
c. PLA through 2.5mm nozzle (fig. 5)
d. PA through 2.5mm nozzle (fig. 6)

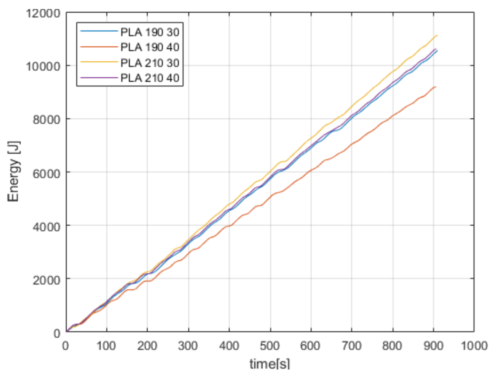

Fig.3. Energy consumption, PLA melting in nozzle 0,8mm

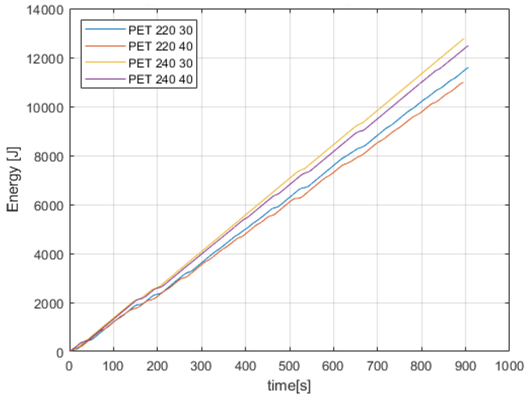

Fig.4. Energy consumption, PET melting in nozzle 0,8mm

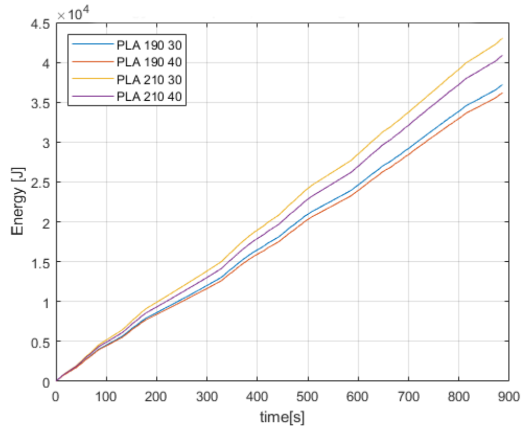

Fig.5. Energy consumption, PLA melting in nozzle 2,5mm

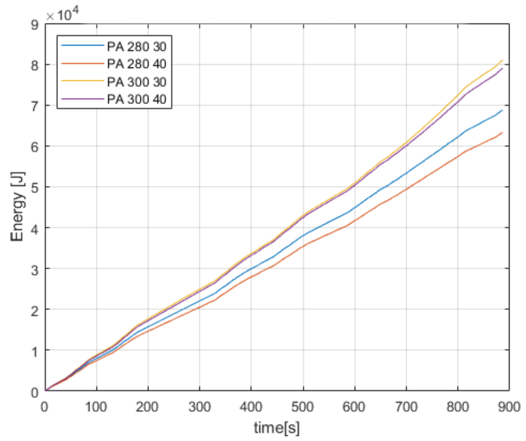

Fig.6. Energy consumption, PA melting in nozzle 2,5mm

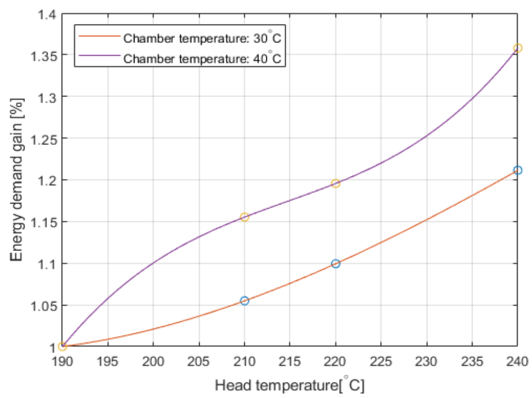

Fig.7. Energy demand gain in ATMAT Signal printer approximation for 0,8mm Nozzle diameter in compatsion to value at 190°C

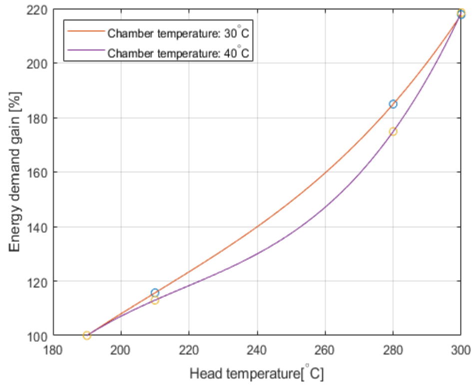

Fig.8. Energy demand gain in ATMAT SATURN printer approximation for 2,5mm Nozzle diameter in compatsion to value at 190°C

Additionally, a graph of an interpolated percentage increase in energy demand at a constant temperature in the printer chamber was presented. When generating the course, a simplification was adopted - the influence of the type of material on energy demand was omitted (the influence of thermal transmittance was ignored), and the only factor was the temperature in the print head.

Discussion and conclusions

The conducted measurements showed an increase in energy demand of the printer head depending on both temperature of the head and temperature in the printer chamber. In case of ATMAT Signal printer and a nozzle with a diameter of 0,8 mm, the average increase in energy demand with an extrusion temperature increase of 20°C was 13%, and in case of new solution and a 2,5 mm nozzle it was 20%, but these values should not be combined due to different measuring points and also because this increase is not linear - a greater change in demand occurs at higher absolute temperature values, especially in the case of new technologies developed for bigger workspaces in this project, where when changing the temperature of the head from 280°C to 300°C, the increase in energy demand reaches even 28.1%.

The temperature change in the working chamber from 40°C to 30°C showed an increase in energy demand by an average of 6,9% for ATMAT Signal printer and 4,8% for research subject. However, the simple dependencies between the influence of the table temperature and the increase in energy demand were not shown (only a significantly smaller dispersion of the increase in new print head and algorithms design (σ = 2,5%) compared to the ATMAT Signal (σ = 4,7%) was revealed), the determination of this impact is planned in correlation with developing stage of research, where it is planned to measure a much larger number of printer parameters.

In FDM type printers, regardless of their size, there is a large number of variable parameters that affect temperature regulation in the head, this temperature has a key impact on the quality of the printed model. It was found that, in addition to the expected temperature in the head (setvalue), the regulation is also influenced by other parameters (e.g. temperature in the printer chamber), hence the conclusion that it is justified to prepare an improved algorithm for regulating temperatures in the printer - one that, contrary to the currently used solutions, will also take into account other relevant parameters.

Another conclusion drawn on the basis of this research is that the influence of parameters on the energy demand of the printer heater is not related in a simple way, but in a more complicated, non-linear way. In further stages of research projects which is focused on further development, the research team carried out further studies on ways to integrate achieved results and the essence their impact in cooperation with the rest of printer construction. Simultaneously further analyzing other parameters on energy demand and quality of temperature regulation.

Article describes results of project POIR.01.01.01-00-2064/15, co-financed by the EU through the National Center for Research and Development.

***Autorzy**: mgr inż. Robert Grolik, AGH University of Science and Technology in Krakow, Department of Manufacturing Systems, al. Mickiewicza 30, 30-059 Kraków, e-mail: robert.grolik@gmail.com; mgr inż. Michał Góra, AGH University of Science and Technology in Krakow, Department of Manufacturing Systems, al. Mickiewicza 30, 30-059 Kraków, e-mail: michal.k.gora@gmail.com; mgr inż. Mateusz Góra, Cracow University of Technology, Department of Materials Science, al. Jana Pawła II 37, 31-864 Kraków, e-mail: mateusz.k.gora@gmail.com; mgr inż. Mateusz Dyląg, Cracow University of Technology, Department of Materials Science, al. Jana Pawła II 37, 31-864 Kraków, e-mail: mateusz.dylag1@gmail.com*

REFERENCES

[1] Budzik G. Siemiński P., *Techniki przyrostowe. Druk Drukarki 3D (2015)*, wyd. Wydanie I, Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.
[2] Liou Frank W., *Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development (Mechanical Engineering)* (2007), „CRC Press; 1st edition".
[3] Website of a manufacturer of 3D printing materials https://eu.polymaker.com (Access: 22.04.2021)
[4] Nieciąg H., Kudelski R., Dudek P., Cieślik J., *An exploratory study on the accuracy of parts printed in FDM processes from novel materials.,* Acta Mechanica et Automatica, 2020 vol. 14 no. 1, p. 59–68.
[5] Grolik R., Duraj R., *Sterowanie wielkogabarytową drukarką 3D z uwzględnieniem innowacyjnego układu ekstruzji i wielostrefowego systemu podgrzewania*, 2017
[6] Loncierz D., Kajzer W., *Influence of 3D printing parameters in the FDM technology on mechanical and utility properties of objects made of PLA – in Polish*, Aktualne Problemy Biomechaniki, (2016), No. 10, p. 43–48
[7] Dudek P., Zagórski K., *Cost, resources, and energy efficiency of Additive Manufacturing*, E3S Web of Conferences, (2017) ISSN 2267-1242, 14, p. 1–8.
[8] Blok L. G., Longana M. L., Yu H., Woods B. K. S., *An investigation into 3D printing of fibre reinforced thermoplastic*, Additive Manufacturing (2018), 22, p. 176–186.
[9] Dougles T. S., Gilbert S.W., *Costs and Cost Effectiveness of Additive Manufacturing*, NIST Special Publication 1176 (2014)
[10] Jerez-Mesa R., Gomez-Gras G., Travieso-Rodriguez J.A., Garcia-Plana V., *A comparative study of the thermal behavior of three different 3D printer liquefiers*, Mechatronics 1-9, 2017
[11] Pollarda D., Warda C., Herrmanna G., Etchesa J., *Filament Temperature Dynamics in Fused Deposition Modelling and Outlook for Control*, Procedia Manufacturing 11, 536 – 544, 2017
[12] Stewart S. R., Wentz J. E. and Allison J. T., *Experimental and Computational Fluid Dynamic Analysis of Melt Flow Behavior in Fused Deposition Modelling of Poly (lactic) Acid*, in ASME 2015 International Mechanical Engineering Congress and Exposition, 2015