CONDITIONING THE STRUCTURE OF DEPOSITED LAYERS BY HYBRID THERMAL SOURCE IN FFF 3D PRINTING

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Abstract. The paper presents the results of some research that aims to highlight the possible changes of the material deposited by 3D printing, when a hybrid heating source is used. The introduction of the second source produces changes in the deposited material, both from the point of view of the mechanical characteristics and from the point of view of the structure of the deposit. The use of an IR lamp to create a hybrid heating system produces a local increase in temperature between 28ºC and 53ºC, for distances between the IR lamp and the piece to print from 200 mm to 400 mm. This increase changes the height and width of the deposit, changes the state of the deposit surface making it less shiny, and changes the edges or limits of the holes, making them clearer. The visual testing and the DSC thermal analysis of the deposited material showed that the effects of these changes are positive, in terms of the decreasing of the discontinuities, and they are negative, in terms of the decreasing of the material plasticity. In conclusion, a hybrid heating during the FFF 3D printing process is possible; important is the appropriate dosage of the additional amount of heat.

Key words: 3D printing, hybrid thermal source, infrared beam, visual testing, DSC analysis, infill density.

1. INTRODUCTION

3D printing is a family of processes for generating shapes by depositing material [1–5]. The deposited materials can be metal, polymers, ceramics, consumables and can be in the form of filament, powder or liquid solution [1, 3, 4, 6]. The deposition process takes place at specific temperatures that allow the deposition material to be in a fluid state, but not necessarily liquid [1–5]. This condition allows it to be deposited with good enough accuracy to respect the conformity of some shapes and sizes.

In the last 15 years, after the expiration of the primary patents from the field of the additive manufacturing, the global market of the consumables for 3D printing

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increased very fast, being estimated at over USD 471 million before the pandemic period [7, 8]. The pandemic kept the scientist in the laboratories and thus the global market is expected to increase at a CAGR of about 19% until 2027 [7–9]. Such growth was possible due to the application of the 3D printing processes in new other domains. It can be found now from domestic to aerospace, communication, and defence industry, and even in bio-technologies [7–10]. Its task is mainly oriented to prototyping [1, 3, 8–10], but fabrication in limited quantities is met, as well [1, 3, 8, 9].

The Fused Filament Fabrication (FFF) process uses polymers as deposition materials [1, 3, 4]. Partially crystalline or amorphous, the respective polymers [1–6], usually used in the form of filaments with the shape and dimensions of the standard section (the usual diameter is 1.75 mm), are brought to the fluid-viscous state by heating in the range of 140–280°C [1–6]. The heating is made with a resistive heat source. The commercial variant of the process ensures the extrusion of the polymer and its placement, on the deposition table or over the previous layer, in the form of strings having an almost circular section. The microscopic image of the deposits highlights this deposit in the form of strings, a deposit that is characterized by a large volume of voids / discontinuities, Fig. 1.

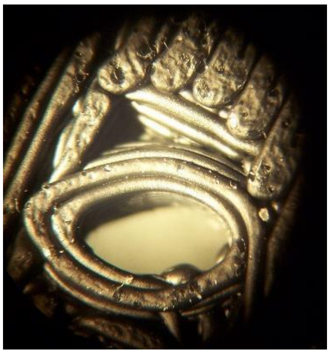


Fig. 1 – Example of FFF deposition using PLA filament.

2. MATERIALS AND EQUIPMENT

According to most of the authors who published comparative studies for different polymers to be used as filaments (examples in [7–9,11]), PLA returns technological and economic and sustainable benefits, higher than other polymers, if used as material for filaments. Being a bio-polymer [10–14] with acceptable values for the main mechanical characteristics (Table 1), it was decided that a commercial PLA filament should be used for experiments.

Polylactic acid (PLA), is a thermoplastic polymer created in the 1930 by the chemist W. Carothers [1], but entered as base material for different products in

1980, when was produced for use by the Cargill company. Actually, PLA is produced by fermenting the carbohydrate from corn starch [14]. The starch is turned into dextrose (D-glucose). The fermentation of glucose produces L-lactic acid, the basic component of PLA [14]. The main characteristics of PLA used for filaments are presented in Table 1.

Table 1

Mechanical characteristics of PLA polymer

Characteristic	Value
Density [g/cm^3]	1,24
Ultimate Strength [MPa]	60–70
Relative elongation [%]	10–12
Young modulus [MPa]	2800–3100
Bending strength [MPa]	90
Brinell hardness [HB]	18–22
Notch impact [kJ/m^2]	5.5–5.7
Flexural modulus [MPa]	1984
Melting point [^{o}C]	150–160

The need for a secondary heating source could be one of the constructive and technological solutions to improve the quality of the joint between two successive layers deposited by printing. This second heat source is expected to keep the layers in the fluid-viscous state for a longer period of time, thus allowing a better cohesion of the successive layers. The action of this secondary source takes place in parallel with the action of the thermal source acting at the hot-end level, creating a synergistic effect with it. The secondary heat source is not a point one, but it will have to be a volume one, in order to ensure the heating of the entire last layer. An action, which is on a 3D surface, cannot be concentrated exclusively on the deposited material, it also acts on the hot-end nozzle and on the heated table on which the deposition is made. The two, however, are powered by automatic power supply control systems. For this reason, for heat additions at the hot-end nozzle and the deposition table that can be compensated by the operation of the adaptive power supplies, the operation of the deposition system will not be affected.

There is a sufficient variety of types of heat sources that could be used for thermal heating. An infrared radiation source was used for the research presented in the paper, as shown in Fig. 2. To a commercial 3D printer, it was attached a source of infrared beam. The source was spatial one, not punctual. Due to these orientations, the infrared light beam acted on the part and on the hot-end and on the deposition bed.

Therefore, the infrared heating was a spatial heating, but due to the position of the IR lamp the heating was targeting the piece (axe of the beam was oriented to the piece).

The amount of heat was adjusted by modifying the distance between the IR lamp and the piece.

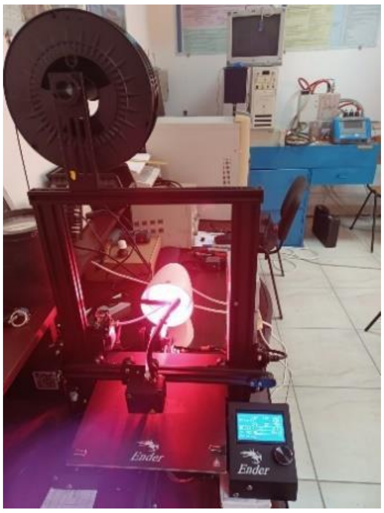


Fig. 2 – Infrared thermal source embedded in the printer structure.

3. EXPERIMENTAL

The experimental research was targeted on the modifications produced by the hybrid heating comparing to the traditional heating for printing. The amount of supplementary heating was adjusted by the distance *D* between the lamp and the piece under building process. Few elements of the thermal field produced during the printing process were determined by measurement, in order to prepare a reference for the future measurement. Measurements in the same points were performed with the IR supplementary heating. The IR lamp was set to 3 different distances: 200 mm, 300 mm and 400 mm. Thus, 3 different quantities of heat were transferred to the piece. The measurement points and the recorded curves are present in Figure 3. For the measurement process IR thermometer was used. Table 2 presents the absolute values of the recorded temperatures, in parallel with the reference values.

Table 2

Mechanical characteristics of PLA polymer

Temperature measured values	IR Distance *D*, [mm]	T_{11} °C	T_{12} °C	T_{13} °C	T_{14} °C	T_{21} °C
Reference (Without IR heating), T_{ref}	N.A.	86	75	73	69	65
Absolute (With IR heating), TabsIR = = $T_{measured} - T_{ref}$	200	53	48	43	38	32
	300	46	46	41	34	31
	400	45	42	41	33	28

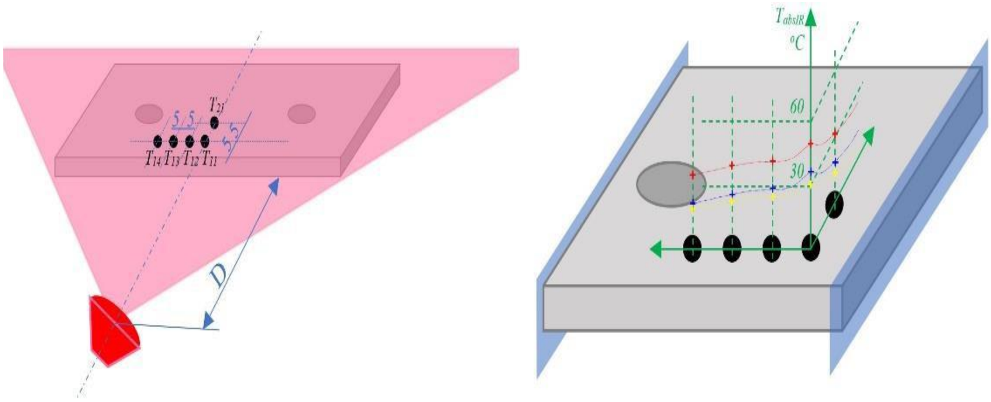


Fig. 3 – Points for temperature measurement a), and the thermal curves b).

It can be observed that the supplementary heat is present and it produces temperatures between 28–53°C, for the distances *D* used.

The variables of the experiment were distance *D* and fill density.

The specimens of printed material were visual tested and Differential Scanning Calorimetry (DSC) analysed, to understand the modifications that occurred for each supplementary heat addition in the hybrid process.

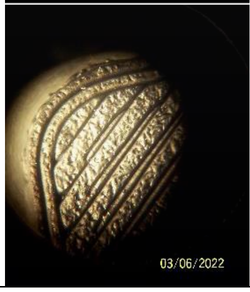
4. RESULTS AND DISCUSSIONS

The visual testing was applied using a stereo-microscope. Specific details of the geometry were targeted and specific aspects of the deposition layers were examined.

Table 3

Results of the visual testing

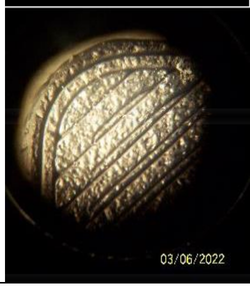
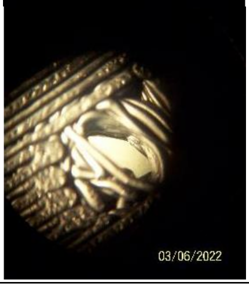
Probe	Printing parameters	Variables		Macrographs (stereo-microscope; same magnitude) 5 mm	
		Fill density [%]	IR – piece distance [mm]		
P50-200	• Hot-end temperature: 210^oC • Bed temperature: 100^oC • Filament diameter: 1.75 mm	50	200		

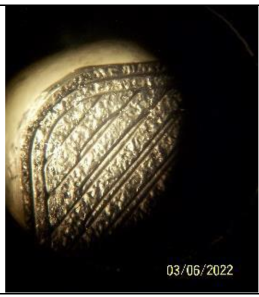
P50-300	• Printing speed: 50 mm/s • Layer height: 0.1 mm • Nozzle size: 0.4 mm		300		
P50-400			400		

Discussions:

1. The deposited strings are lower in height as the distance *D* decreases.
2. The deposited strings are wider as the distance *D* decreases.
3. The deposited strings are less shiny as the distance *D* decreases.
4. The channels between two strings become less wide as the distance *D* decreases.
5. The edges of the holes are more clear and compact as the distance *D* decreases.

The external appearance of a deposit with 50% fill density, under the conditions of additional IR heating with the source located at 200 m, has a high degree of similarity with the external appearance of a deposit with 100% fill density, but without additional heating. The additional heating makes the deposited string better cover the previously deposited layer.

P100-200	• Hot-end temperature: 210^{o}C • Bed temperature: 100^{o}C • Filament diameter: 1.75 mm • Printing speed: 50 mm/s • Layer height: 0.1 mm • Nozzle size: 0.4 mm	100	200		
P100-300			300		

P100-400			400		
Discussions: 1. All discussions presented above, for 50% fill density, are available for 100% fill density, as well 2. Material compaction increases as the distance *D* decreases.					

DSC analysis was performed by using a NETZSCH HP Phoenix 204 equipment. The investigation of the specimens was done in the folowing conditions: the heating and the cooling were done in argon atmosphere; the heating started at 24°C with a rate of 10°C /min and ended at 224°C; the cooling had the same rate and was conducted to –80°C; after a keeping time at the lowest temperature, the specimens were reheated up at 400°C with a rate of 10°C/min. Elongation viscosity was the subject of the investigation, in order to understand the modification of the material flowing due to the supplementary heat brought by the second thermal source from the hybrid system of heating.

Figure 4 shows the curves that describe the behaviour of the material, for the 3 distances of irradiation, against the reference material.

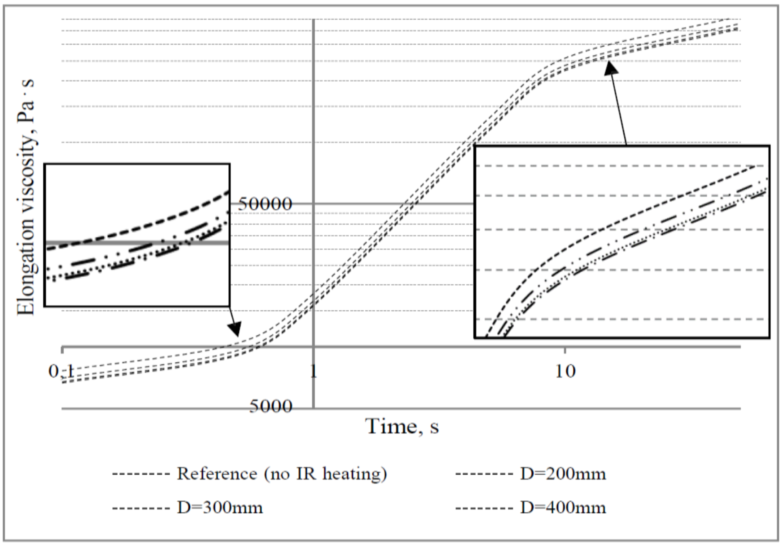


Fig. 4 – Modification of the elongation viscosity.

It can be observed in Fig. 4 a decreasing of the elongation viscosity as the distance *D* decreases. This means an increase in the rigidity of the polymer material. The modification can be useful in different applications, in which a higher stiffness is desired. The difference between the effects of the supplementary heating when the IR source is at 300 mm and at 400 mm is very low. This means that above 300 mm distance from the piece, the effect of the supplementary heating is almost inexistent.

5. CONCLUSIONS

FFF is a printing process used to produce pieces by addition of material. The deposition has shape of a string. Such shape involves large volumes of discontinuities.

Hybrid heating, using a second thermal source in parallel with the traditional resistive one, is expected to bring modification of the deposited material. The modifications would be in terms of characteristics and structure of the deposition.

IR lamp is a potential heating source to be added in a hybrid system of heating. The heating is a spatial one, and the entire surface that is the support for the deposition receives supplementary amount of heat from it.

The main modifications recorded during the hybrid heating FFF printing are related to:

- the height of the deposited string is lower with the increasing of the supplementary heat;
- the width of the deposited string is wider with the increasing of the supplementary heat;
- the shininess of the deposited string enters to regression;
- the shapes become clearer.

The material suffers after the deposition process an increasing in stiffness, which involve a decreasing of the plasticity of the final product.

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