Additive manufacturing of polylactic acid (PLA) material considering preheating uncertainty effect

Fabrication additive de matériau à base d'acide polylactique (PLA) en tenant compte de l'effet d'incertitude du préchauffage

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ABSTRACT. The main objective of this research is to define the best strategies to contribute to the industrialization of the Additive Manufacturing (AM) technology. The industrialization of AM needs to perform several research to deal with the different failure scenarios. The high failure rate leads to arise the total cost which can be a big obstacle to industrialize the AM technology. So, the different failures should be first identified and next treated. The uncertainty should be considered at several levels such as filament material properties, shape complexity, AM process... One of these uncertainty sources is preheating where a failure scenario can be occurred because of preheating issues which related to AM process parameters. In fact, the preheating plays an important role at the adhesion levels, especially at the beginning of the AM process. Considering the preheating uncertainty should lead to increase the reliability level of the AM processes. To highly increase the preheating temperatures, the quality of the products may be affected such as their surface quality and final dimensions. So, there is a need to perform a statistical study considering different preheating parameters. In this work, a complex shape is considered to perform several studies at different preheating temperatures. This complexity of the studied example necessitates to add some supports to obtain the required geometry. An experimental study on PLA (Polylactic acid) material is carried out to define the most reliable preheating parameters for different models. According to the present example and several realistic applications, it is concluded that when manufacturing PLA materials, the best choices of the preheating temperatures are 240°C for the extruder and 100°C for the platform. This way we reduce the likelihood of failure due to adhesion issues. The preheating temperatures largely affect the adhesion levels at the beginning of the AM process. Even for the same conditions, there is no guarantee to obtain the same results which leads to consider the uncertainty concept at each level of the AM process. In addition to the different findings of the preheating effect, this paper provides the newcomers to AM area with some basic concepts and several probable failure scenarios in a simple way.
KEYWORDS. Additive manufacturing, Uncertainty, Polylactic acid (PLA), Failure scenario, Tree-like support, Linear support.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, rapid prototyping, is a quick developing technology having the opportunity to transform next-generation manufacturing. 3D printing (or AM) builds up solid objects layer by layer in a manner like a 2D printer with the "printed" layers arranged on top of each other (Gebhardt and Fateri 2013). There are a lot of AM techniques such as Fused Deposition Modelling (FDM), Stereolithography (SLA), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). AM processes are based on the layer-by-layer material deposition or solidification, which eliminates the geometric complexity limitations to a large degree (Liu et al. 2018). The AM technology has gained important academic as well as industry interests because of its ability to create complex shapes with customizable material properties (Gao et al. 2015). It can be called a free-form manufacturing technique where topology optimization layout can be realized without considering shape or sizing optimization processes (Kharmanda and Antypas 2020). In addition, topology optimization can be used to solve several challenges in AM (Pradel et al. 2018; Fu 2020). Along the last decade, several review articles have been published about the use of optimization methods in AM process (Wong and Hernandez (2012); Frazier (2014), Shashi et al. (2017); Wiberg et al. (2019); Alfaify et al. (2020).

For complex geometries, there are many problems may occur when using the conventional manufacturing. AM provides the opportunity to perform the fabrication in a simple and effective way despite there are several difficulties, especially high costs and waste of materials. So, there is a strong need to overcome several challenges when integrating the AM into the industrial production. Certain AM companies honestly mention that despite it is almost three decades after the AM innovation, the AM could not be regrettably industrialized. The main difficulty can be represented by a big number of trials to provide good quality products. In general, a manufacturing strategy can be industrialized when many parts (thousands) can be produced. The increase of failure rate level in the AM leads to an increase of production costs. Therefore, it is better to simulate and/or control the AM process before in order to reduce the likelihood of failure. It is also probable to get unexpected problems during the AM process. It is difficult to guarantee the properties of the final products such as surface roughness, porosity, fatigue, durability... Therefore, it is currently challenging to industrialize the AM technology. There is a strong need to consider the uncertainty concept to solve or reduce these problems with the object of industrializing the AM.

There are a lot of sources of uncertainty when performing AM processes and it is important to evaluate the different risks resulting from these uncertainties. For example, geometric uncertainties may lead to manufacturing imperfection. This way, we get some deviations from the as-designed geometry (Liu et al. 2018). Another type of uncertainty concerns material uncertainties. In fact, the material properties are related to several parameters such build direction, orientation, extrusion etc. The material property uncertainties also affect the fabrication cost. So, we need to elaborate an effective AM framework to solve these kind of problems (Li and Tsavdaridis (2021); Ribeiro et al. (2021)). There are several types of uncertainties, however we deal in this work with thermal uncertainties. The thermal uncertainties can be found at the preheating level as well as during the AM process. In this work, we only study the preheating uncertainties regarding the temperature of the extruder and the platform (build plate) at the beginning of the AM process.

2. Materials and models:

In this section, we first describe the studied geometry and the different issues related to this geometry. Next, the used filament material and the 3D printing machine are described. Finally, the different failure scenarios are treated in order to define the nature of expected uncertainties.

2.1. *Studied geometrical model:*

The used model is called Hilber Cube in STL version, available on FLASHPRINT software. The dimensions are minimized with the object of decreasing the AM process time consumption. The used software provides the possibility to change the scale and the rotation of the product in the three directions (X, Y, Z), to cut and duplicate to several parts which is helpful to simulate and/or control the AM process before starting to build the model.

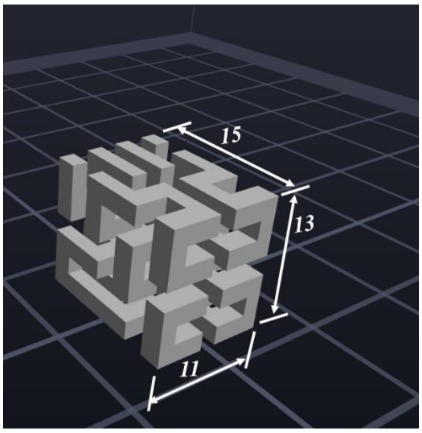


Figure 1. *Main dimensions of the studied Hilber Cube*

All these possibilities should be used in a correct way to avoid the waste of materials and time. Furthermore, this minimization of dimensions is very helpful to reduce any potential bending failure scenarios when dealing with large surfaces. The main dimensions (length, height, and width) are illustrated in Figure 1. For complex geometries, the AM process cannot be performed without supports when having overhanging features (Jiang et al. 2018). According to the laws of gravity, it is not possible to extrude the filament in the air. So, the support structures are necessary to continue the AM process. The supports affect the AM cost and time and may lead to problems in the finished surfaces of the products. These support structures should be removed slowly and carefully by using suitable tools (needles, knives, pliers, cutters …) which should be selected according to several criteria such as size, shape, material ... In Figure 1, there are many overhanging features which necessitates to add some supports.

2.2. *Effect of skirt/brim/raft*

A skirt is an outline which surrounds a part (or the whole) of the printed structure but does not touch it. It is extruded on the print bed before moving to print the model. In addition, it serves a useful purpose because it helps prime the extruder and establish a smooth flow of filament. The brims or rafts can be also utilized in 3D printing applications. The brim consists of a single layer and can be increased up to five layers with the same parameters (speed, dimensions …). However, the raft consists of three types of layers with different parameters: bottom, middle and top layers (at least two types: bottom and top layers). The bottom layer is a single layer with several parameters regarding the dimensions (Layer Height and Path Width), speed and infill density. While the top layer can be increased to be four layers with several parameters regarding the dimensions (Layer Height, Path Width, Angle Between Model), speed and infill density. There is a possibility to add up to three layers as middle layers with several parameters regarding the dimensions (Layer Height and Path Width), speed and infill density. These different parameters allow the user to control the adhesion levels considering the effect of these parameters to balance between the adhesion issue and the time consumption. The former can typically choose the best between brims and rafts with the object of balancing between cost and time consumption. Rafts lead to better adhesion, for example, than brims since they are located underneath the printed model to improve adhesion. The raft and brim arise the cost and manufacturing time consumption. In complex configurations, there is a need to add raft or brim. However, when increasing the nozzle and the platform temperatures, we can perform more complicated configurations without adding neither raft nor brim. This observation can be noted from the results of this research where the preheating temperatures of the platform and extruder play an important role.

2.3. *Used filament material:*

Several types of filaments can be used for AM products: Polylactic acid (PLA), ABS (Acrylonitrile Butadiene Styrene), Polyethylene Terephthalate Glycol (PETG) ... (Shi et al. 2021). The used PLA filament here is being a biopolymer obtained from corn starch or sugar cane. This kind of biopolymers is considered as renewable resource which means sustainable material. In addition, several advantages can be found:

– non harmful material,
– nontoxic material,
– environment friendly material,
– good material toughness,
– good material strength,
– low material shrinkage,

...

According to manufacturer of the used PLA filament in this work, the print temperature should belong to the interval 190-220°C and the storage temperature should not exceed 50°C. During the AM process, we fix the temperatures of the extruder to be 210°C and of the platform to be 50°C. Several recent papers and reviews can be found in literature regarding the temperature effect on the PLA mechanical properties (Grasso et al. 2018; Jayanth et al. 2021; Hsueh et al. 2021). The temperature effects of several mechanical properties of PLA such as Young's modulus, ultimate tensile strength, strain at failure and stress at failure are studied in Grasso et al. (2018). In addition, Jayanth et al. (2021) found that these properties, particularly, tensile properties can be largely improved by heat treating. When comparing these properties with other type of filament such as PETG, Hsueh et al. (2021) found that the PLA mechanical properties of are better than those of PETG, but the thermal deformation is the contrary.

2.4. *Used 3D printer:*

The used machine is called ADVENTURER 3, manufactured by FLASHFORGE. It uses FFF (Fused Filament Fabrication) as a print technology. The build volume is 150×150×150mm and the filament diameter is 1.75±0.07mm. The nozzle diameter is 0.4mm and the layer resolution belongs to [0.1-0.4]mm. So, too thin layers cannot appear in the final products which leads to a lack in the final products. The build speed belongs to [10-100]mm/s and the build accuracy is ±0.2mm. The default preheating parameters are 220°C for the extruder and 50°C for the platform. According to the extruder heating, two types of extruders can be used to attend the temperatures 240 and 265°C, respectively. The maximum temperature of platform heating is 100°C. Here, we fix the temperatures of the extruder and the platform during the AM process to be 210C/50°C (default values provided by software for PLA filament). It is recommended by the manufacturer to use this 3D printer (ADVENTURER 3) to print PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) filaments which are the common 3D printed materials. It is also recommended to use PLA filament since it is a non-toxic material, while ABS filament will give off certain poisonous gas when heating up.

2.5. *Probable failure scenarios:*

To carry out a labour, several problems may occur and lead to a waste of materials and time, especially when repeating the AM trials. These problems should be considered as important reasons to adopt the AM technology in the industrial areas. Failure scenarios can be happened because of several causes:

- Geometry complexity: Support structures should be provided in certain complex geometries (overhanging features) during the AM process. To avoid the waste of materials and repeated trials, it is recommended to consider the raft and to arise the temperature of the platform during the manufacturing process.

- Additive manufactured material quality: To avoid the waste of materials and repeated trials, it is better to select a material of a good quality.

- Preheating of extruder and platform: Some manufacturers propose to use glue to improve the adhesion level, however we consider that this solution may affect the platform quality in the future operations. So, it better to increase the preheating temperature of the extruder and platform.

- Platform heating during the AM process: To avoid the waste of materials and repeated trials, there is a need to arise the temperature of the platform during the AM process.

- Extruder heating during the AM process: To avoid the waste of materials and repeated trials, there is a need to arise the temperature of the extruder during the AM process. However, there is a limitation of this increase to avoid environmental and product quality issues.

- Filament supply speed: This parameter affects the AM process and the product quality. A suitable filament supply speed leads to smooth surfaces and process stability.

- Dimension homogeneity: For large dimensions, there may be adhesion issues in certain point because the applied forces can produce a bending moment which leads to separate even the raft from the platform.

In this work, we carry out an experimental study on the preheating uncertainty effect of the extruder and platform temperatures at the beginning of the AM process.

3. Results:

At the beginning, an AM process started for the studied Hilber Cube without any supports to show the effect of the overhanging features. Next, two support types are used: linear and tree-like supports. For each support, three slicing configurations are modelled. These models are respectively called here, rafted, brimmed, and skirted slicing models. For the first and second slicing models, skirts are automatically produced to start the AM process.

3.1. *AM process without supports:*

At the beginning, the studied Hilber Cube is sliced without any kinds of supports as shown in Figure 2 where a raft is added to the studied model. Figures 3a, b, and c show a resulting 3D printed Hilber Cube, a disordered region, and a clarification of disordered region, respectively. The resulting 3D printed structure in Figure 3, does not look like the required Hilber Cube as in Figure 1. So, the supports play an important role in assisting printability in the AM process.

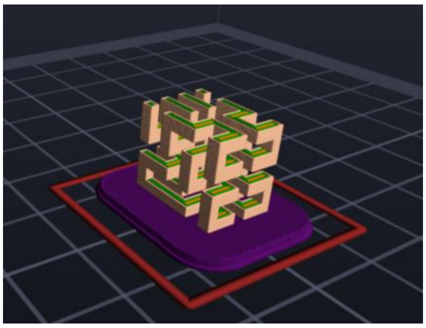
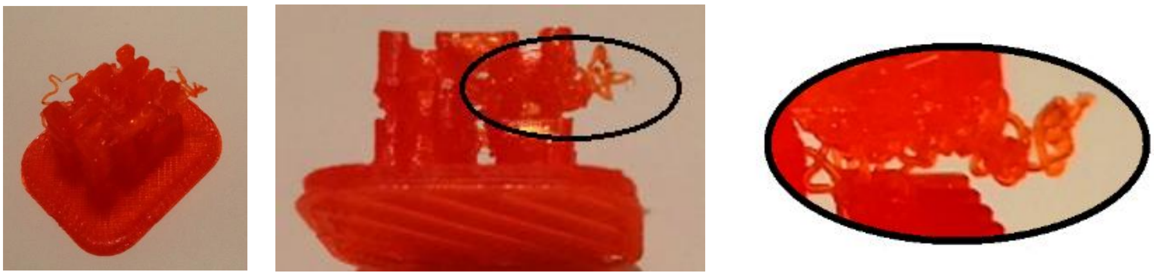


Figure 2. *Rafted slicing model without support.*

When a 3D model has overhanging features, there is need to support structures to allow these features to be able to stand in the air according to the gravity laws. So, there is a need to provide supports during the AM process.



a b c

Figure 3. *a) Resulting 3D printed Hilber Cube, b) Disordered region, and c) Clarification of disordered region.*

3.2. *AM process with supports:*

Several types of supports can be found in literature such as Linear supports, Bridge-like supports, Tree-like supports, Fence supports, Lattice supports, Cellular supports ... (Dumas et al. 2014; Vanek et al. 2014; Jiang et al. 2018). However, two types of supports are only available in the used slicing software (FLASHPRINT): Linear and Tree-like supports.

3.2.1. *Linear supports:*

Figure 4 shows the studied Hilber Cube with linear supports where only two parameters can be considered: the overhang threshold which belongs to the interval [20°-85°] and the pillar size which belongs to the interval [1-8mm].

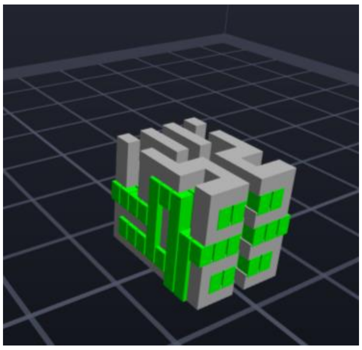
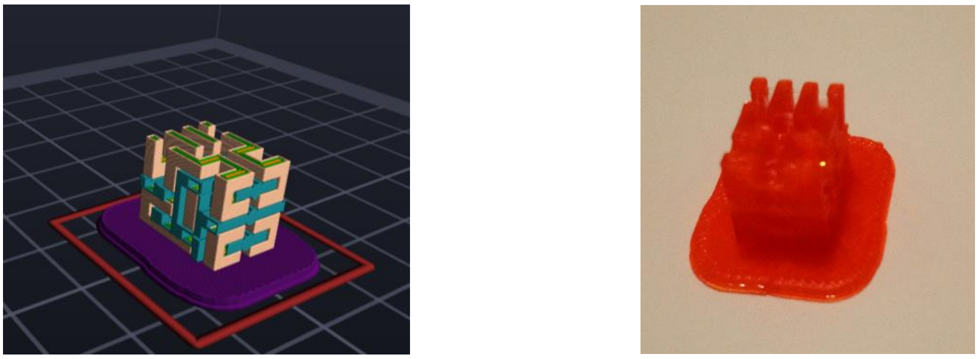


Figure 4. *Studied Hilber Cube with linear support.*

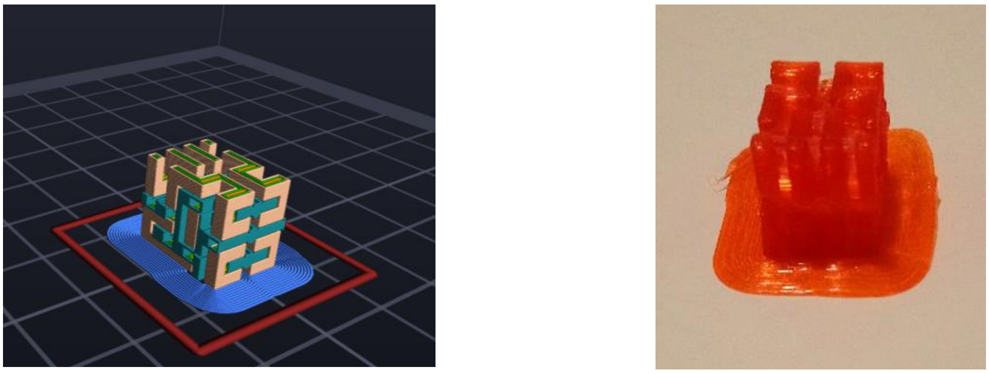
The default values are considered here where the overhang threshold is 55° and the pillar size is 1.5mm. The effect of these two parameters can be modified according to the previous intervals to reduce the support volume. However, we focus here only on the preheating parameters and use the default parameters for support since it is not the objective of this work to deal with the support parameters. Figures 5a and b show a rafted slicing model with linear support, and the resulting rafted 3D printed Hilber Cube with linear support, respectively. In Figure 5a, the AM process starts with a skirt which surrounds the whole of the printed model, and the raft starts next.



a b

Figure 5. *a) Rafted slicing model with linear support, and b) Resulting rafted 3D printed Hilber Cube with linear support.*

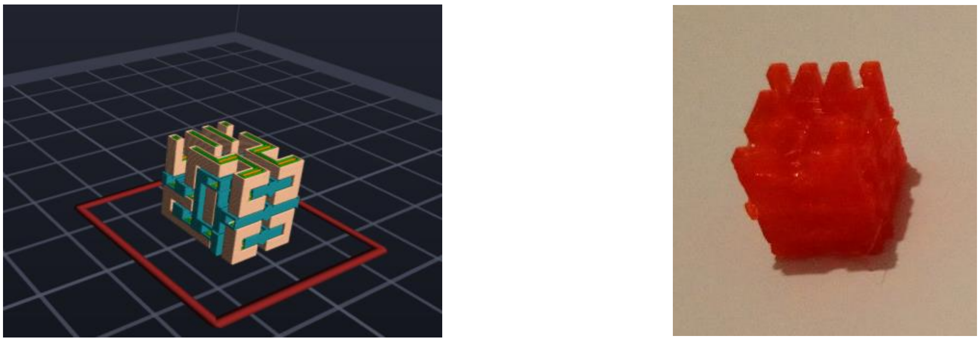
Figures 6a and b show the brimmed slicing configuration with linear support, and the resulting brimmed 3D printed Hilber Cube with linear support, respectively. In Figure 6a, the AM process also starts with a skirt which surrounds the whole of the printed model, and the brim next starts.



a b

Figure 6. *a) Brimmed slicing model with linear support, and b) Resulting brimmed 3D printed Hilber Cube with linear support.*

Figures 7a and b show a skirted slicing with linear support, and the resulting 3D printed Hilber Cube with linear support, respectively. The skirt surrounds the whole printed part in the slicing model in Figure 7a, while it removed from the resulting printed part in Figure 7b when separating the printed object from the platform (build plate).



a b

Figure 7. *a) Skirted slicing model with linear support, and b) Resulting 3D printed Hilber Cube with linear support.*

Table 1 shows the different preheating results of Hilber Cube with linear support. When the failure happened, several trials can be carried out before excluding the results. For example, when considering the rafted case, there is no failure even at lowest used temperatures (200/50°C). However, at the same temperature, three failure trials have been performed for the brimmed case without any successes. Next, a single failure trial has been carried out for the skirted case because there is no adhesion surface. When increasing the extruder temperature at the preheating level, three failure trials have been performed at the temperatures 220°C, without any successes for the brimmed configuration. However, at the temperatures 220/100°C, after a couple of trial, a single successful trial has been found as shown in Table 1.

Temperatures	**z**	200°C	200°C	220°C	220°C	240°C	240°C	265°C	265°C
	Platform	50°C	100°C	50°C	100°C	50°C	100°C	50°C	100°C
Models	***Rafted***	OK	OK	OK	OK	OK	OK	OK	OK
	Brimmed	3F	OK	3F	F+OK	F	OK	F	OK
	Skirted	F	2F	F	OK	F	OK	F	OK

Table 1. *Different preheating results of Hilber Cube with linear support.*

3.2.2. *Tree-like supports:*

Figure 8 shows the studied Hilber Cube with tree-like support where four parameters can be considered: the overhang threshold which belongs to the interval [20°-85°], the post diameter which belongs to the interval [1-6mm], the base diameter which belongs to the interval [3-10mm], and the base height which belongs to the interval [0-10mm]. The default values are considered here where the overhang threshold degree is 55° and the other corresponding dimensions are: 3.0, 6.0 and 6.0 mm for the post diameter, the base diameter, and the base height, respectively.

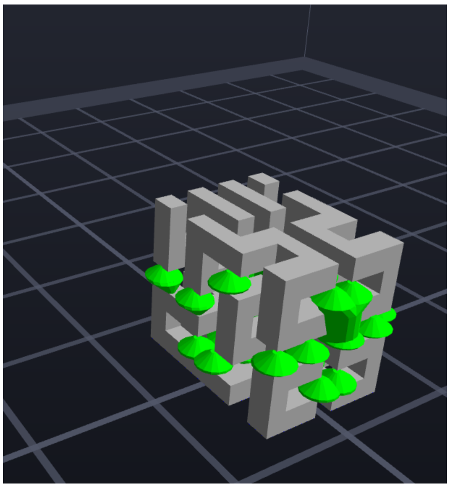
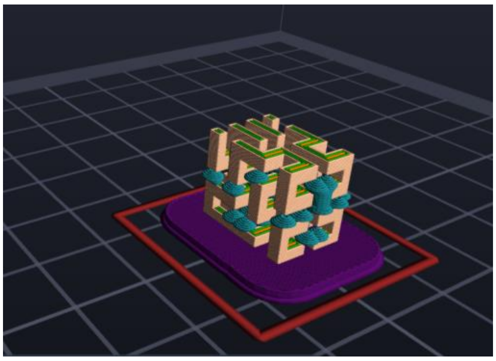
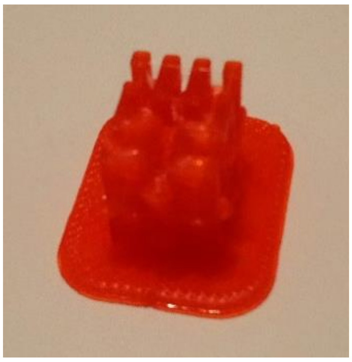


Figure 8. *Studied Hilber Cube with tree-like support.*

The effect of these four parameters can be modified according to the previous intervals to reduce the support volume. In this work, we fix the default values for the support and focus only on the preheating parameters. Figures 9a and b show a rafted slicing configuration with tree-like support, and the resulting rafted 3D printed Hilber Cube with tree-like support, respectively. In Figure 9a, the AM process starts with a skirt which surrounds the whole of the printed model, and the raft next start. When separating the resulting printed part, the skirt is removed, and the resulting configuration is shown in Figure 9b without skirt.



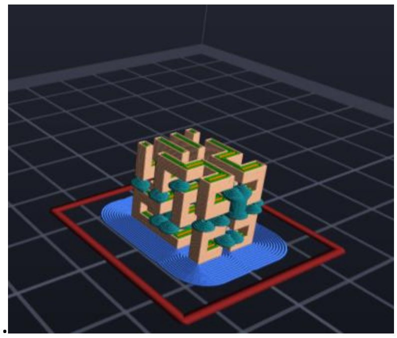
a



b

Figure 9. *a) Rafted slicing model with tree-like support, and b) Resulting rafted 3D printed Hilber Cube with tree-like support.*

Figures 10a and b show a brimmed slicing model with tree-like support, and the resulting brimmed 3D printed Hilber Cube with tree-like support, respectively. In Figure 10a, the AM process starts with a skirt which surrounds the whole of the printed model, and the brim next starts.



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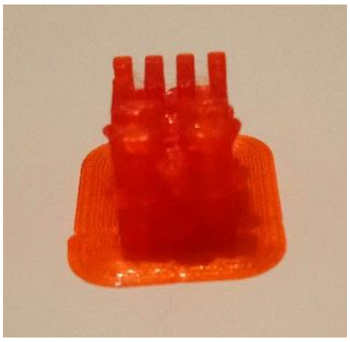
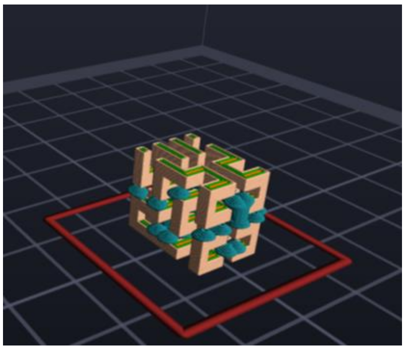


b

Figure 10. *a) Brimmed slicing model with tree-like support, and b) Resulting brimmed 3D printed Hilber Cube with tree-like support.*

Figures 11a and b show a skirted slicing configuration with tree-like support, and the resulting 3D printed Hilber Cube with tree-like support, respectively.



a

b

Figure 11. *a) Skirted slicing model with tree-like support, and b) Resulting 3D printed Hilber Cube with tree-like support.*

Table 2 illustrates the different preheating results of Hilber cube with tree-like support. At the temperatures 200/100°C, after three failure cases, we get a single successful case for the brimmed slicing model. At the temperatures 220/50°C, after a single failure case, we get a successful case for the rafted slicing model. At the temperatures 220/100°C, after three failure cases, we get a successful case for the rafted slicing model.

Temperature	**Extruder**	200°C	200°C	220°C	220°C	240°C	240°C	265°C	265°C
	Platform	50°C	100°C	50°C	100°C	50°C	100°C	50°C	100°C
Model	**Rafted**	OK	OK	F+OK	3F+OK	OK	OK	OK	OK
	Brimmed	F	3F+OK	F	OK	F	OK	F	OK
	Skirted	F	F	F	OK	2F	OK	F	OK

Table 2. *Different preheating results of Hilber cube with tree-like support.*

4. Discussion and conclusion

According to the difference results, the preheating clearly affects the AM process when considering different slicing models: rafted, brimmed, and skirted slicing models. When increasing the preheating temperatures (especially for the platform), there is a big potentiality to increase the adhesion level and stability. When the preheating temperature of the platform equals to 50°C, the rafted slicing model is the only model which can be printed. When this temperature becomes 100°C, the brimmed slicing model can be printed. However, both preheating temperatures of the extruder and the platform affect the adhesion level for the skirted slicing models. In this case, the preheating temperatures should be 100°C for the platform and at least 220°C for the extruder.

In addition, the type of support structures may affect the results. For tree-like supports, the likelihood of failure is higher than linear supports. As shown in Table 1 for linear support results, only a couple of trial are performed at the temperatures 220/100°C and one of them succeeded. Despite these two trials are submitted to the same conditions (preheating temperatures, adhesion surface ...), one of them succeeded. Here, the uncertainty concept should be considered. On the other hand, we have more cases for tree-like support results at the preheating temperatures: 200/100°C for the brimmed slicing model, and at the following preheating temperatures: 220/50°C and 220/100°C for rafted slicing models. The preheating conditions can affect the stability of AM process, especially at the starting moments. Some companies provide instruction to use the glue for adhesion purposes. However, this may affect the quality of the platform surface when removing the glue each AM operation. So, we do not recommend to use glue at the beginning of the AM process. According to this work, the preheating leads to good adhesion results and we then recommend that the preheating temperatures to be 240°C for the extruder and 100°C for the platform. Several trials and realistic examples confirm this recommendation. The preheating helps in reducing the likelihood of failures, which reduces the fabrication costs. In the future work, a statistical study should be carried out to describes how uncertainty analysis can be incorporated into the thermal AM studies. In addition, effect analysis of the different parameters influencing the adhesion levels should be carried out in detail in order to establish an optimum strategy to industrialize the AM technology.

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Conflict of Interests

The author declares that there is no conflict of interests.

List of Abbreviations:

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
PETG	Polyethylene Terephthalate Glycol
PLA	Polylactic acid
SLA	Stereolithography

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