Materials Research Proceedings 41 (2024) 2-11 https://doi.org/10.21741/9781644903131-1

Modeling fused deposition of PLA by analysis of the layers

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Keywords: FDM, PLA, Finite Element Analysis, Analytical Modeling

Abstract. The realization of the additive manufactured components requires the understanding of the variables having an effect on the physical final geometry. One of them is represented by the initial digital information with required tolerance, in particular where the different parts such as planar and curved ones need to be connected together. The other important variable is represented by the extruding conditions in FDM of PLA blend materials. The temperature setting with which to reduce the induced tensions, the volume variation and warpage is determined.

Introduction

The realization of the additive manufactured components requires the understanding of the variables acting on physical final geometry. One of them is represented by the initial digital information representing the physical model in particular in those parts where planar and curved geometries need to be connected together. That is why the whole geometry represents generally the main variable by which to give a object with or without supports during building.

The other important variable is temperature and then the cooling conditions and subsequent volume variation of the physical model produced. The global effect could be in the range of some hundreds of microns that risks to be not so much lower than layer thickness. Some of such details are reported in [1] and by the author in previous works [2, 3] in which it was found that quantifying the amounts of such approximations avoids undesired dimension errors in the components [4-8] also due to the typical behaviour of each material during or after printing.

Up today different materials can be applied in the field of the additive manufacturing technology such as polypropylene (PP) and polyamide materials, PEEK, polyethylene, PVC and PolyLactic Acid (PLA) under different conditions [4-5]. In detail, polyamide and PLA are materials generated by natural resources and sometimes with addition of solid particles in order to obtain a desired pigmentation and/or to increase chemical and physical properties sometimes depending to ageing as for some metals. In particular the use of PLA blend materials under different conditions can be made in all of the situations in which appearance and resistance, very similar to other better known polymers such as PP, needs to be reached. Some of these materials are suitable for injection molding that was representing in the past decades the most popular way to produce polymer components with high productivity and low cost. Of course the continuous demand for a long time utilization of single or prototype units have given to the rapid technologies with suitable materials the task to shorten boring and time consuming procedures. In order to realize conceptual and ergonomic physical parts with materials able to perform in service applications under given and stable conditions. In fact, they can be considered in their different composition and treatments for many applications by the beverage to other daily ones.

The fast realization by FDM notwithstanding the initial digital design and tuning of digital data, particularly intensive for additive manufacturing, gets such technology comparable to largely applied injection molding techniques by which to realize long duration manufacts.

Understanding the amount of approximations when new materials in conjunction with FDM in building some kinds of geometry represents a must also when components are made for prototyping purposes. In the past the author and coworkers considered very complex geometries

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[2,3] but the problem in general in reaching the required specification remains when the curved parts are connected with planar ones. The details at the interlayer level in FDM building can be found in [9-12] where the problems arising needs to be further investigated. The use of additive manufacturing techniques in realizing curved parts is still today under studying for the problem of the realization with a reduced number of additional supports responsible for the increase of processing time due to the removal and treatment of surfaces in particular for material such as PLA, PLA-blend or recycled PLA. At the same time performing the objective to reduce machining phases to obtain the dimensional and surface requirements. To do so efforts are required to determine the conditions in terms of different variables influencing the result.

The present study aims at proposing a methodology to design and realize curved parts connected with planar ones in order to match the requirements of the project with reduced use of additional supporting material during building avoiding then the subsequent surface treatment. To do that the digital information needs to be managed in order to avoid too much high connection angle values with the control on the curved zone and on volume variation during artificial cooling by calm air or during vacuum cooling. It was found that without platform heating the calm air condition is able to determine layer temperatures at which shrinkage, warpage and tensioning can be reduced with a low effect on the final geometry.

Modeling and experiment procedures

The objective is to realize a geometry characterized by a planar part connected with a simple curved following the proposed methodology reported in Fig. 1.

The digital model is characterized by a plan connected with a semicylinder shown in Fig. 2. The nominal dimensions are 100 mm in length, 80 mm in width with a height of the dome of 25 mm being the geometry considered in the digital CAD system. It was obtained after the proper definition of the arc geometry, of the connection to the planar basis and of the modeling of the layer to layer temperature during building considering artificial and vacuum cooling of the object and related tensional state. By the numerical modeling the temperature distribution and volume variation on the under building different parts are given at related layer thickness and extruder velocity. The FDM realization of the physical model in PLA blend material was performed under the described conditions.

In particular during the preliminary design phase two kinds of arc were used to represent the dome. The difference can be observed in Figs. 2 and 3 where two tolerance amounts and sketching strategies characterized by a different discretization of the dome are used and then converted in STL of the object to be realized. In Fig. 3a) a too severe tolerance of 0.001 mm between the curved top of the part and the vertical planar one is used giving an appearance of a not well defined object. Increasing the tolerance over than 0.01 mm the STL in the Fig. 3b) is obtained in which the different sketching strategy characterized by an increased number of reference points along the arc is also applied.

Fig. 4 shows the connection angle of 70° between the dome (intended in the lateral curved part of the object) and the planar basis. The base has a thickness of 10 mm with a 15 mm height for the dome. This connection was used instead of that of 90° and checked with preliminary FDM tests in order to avoid physical supports and layering errors in physical building. Even if the standard triangulation admits that angle.

The physical model realized by FDM got the dimensions of 50 mm, 40 mm and 12.5 mm respectively to reduce material consumption and time to objecting. The nominal layer thickness used was 0.2 mm with a filament in blend PLA material and a temperature of the extruder between 225° and 245°C selected. The scanning velocity of the extruder not higher than 100 mm/s during working and than 150 mm/s in idle movements. Such velocity values were decreased for scaled physical model in order to reduce the amount of the cartesian portal vibrations, while the temperature a bit increased to follow the geometry of connections. In order to understand the thermal behaviour the analytical modeling in describing temperature decrease was used.

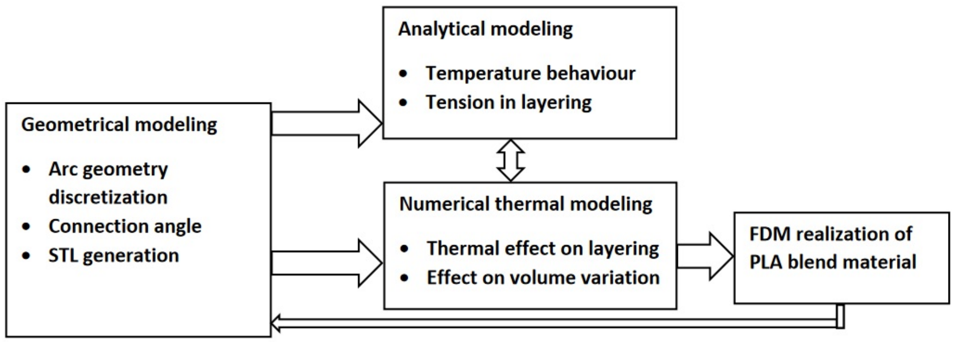


Figure 1. Methodology proposed for the study.

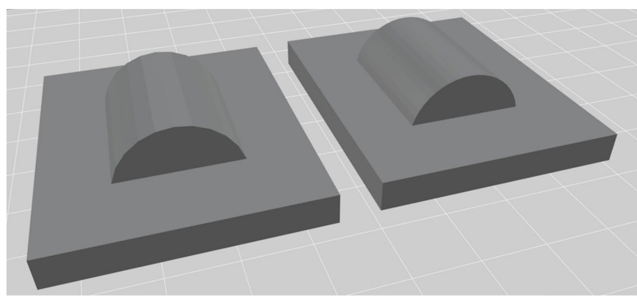


Figure 2. Two kinds of arc described for the dome of the physical object: the discretized arc from the left and less discretized one.

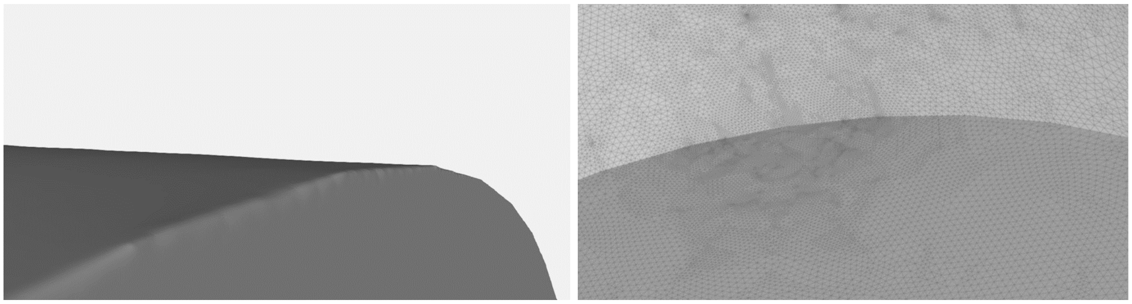
The temperature behaviour was modeled, considering similar problems reported in [13] based on the heat balancing, by the analytical study in which the temperature decrease over the time is described by the adapted equations:

$$T_{layer} = T_{p.layer} + \left(T_{layer\ i.} - T_{p.layer}\right) \cdot \exp\left(\frac{\alpha A(t_0 - t)}{\rho c V}\right) \quad (1)$$

$$T_{p.layer} = T_{b.} + \left(T_{p.layer.i} - T_{b.}\right) \cdot exp\left(\frac{\alpha A(t_0 - t)}{\rho c V}\right) \quad (2)$$

where:
T_{layer} : temperature of the actual layer
$T_{layer\ i.}$: initial temperature of the actual layer at the time t_0
$T_{p.layer}$: temperature at previous layer at the time t_0
$T_{p.layer\ i.}$: temperature at previous layer
$T_{b.}$: temperature at the basis (room temperature)
α: thermal heat exchange coefficient
A: contact surface
ρ: density of material
c: specific heat of PLA
V: volume

t: actual time
t_0: time of the deposition of the actual layer.



a) b)

Figure 3. Particular of the arc in the CAD environment with a connection tolerance of 0.001mm between the vertical planar part and the top curved one (a) and with a smoother tolerance and a different sketching strategy in the STL standard (b).

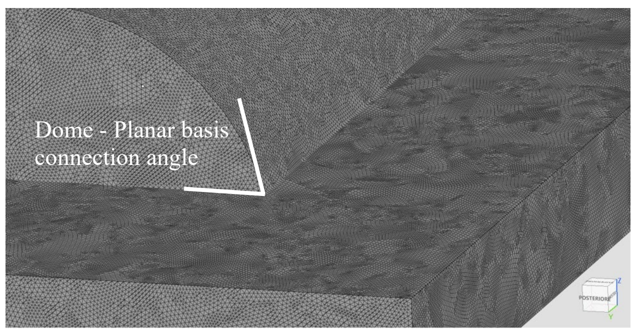


Figure 4. Connection angle between the curved and the planar parts of 70°.

Eq. (1) being the temperature decrease law of the actual layer to the solid layer previously deposited while eq. (2) the description of the temperature decrease close to the environment temperature value. But at the very early moments the temperature behaviour can be better explained by the heat balancing fluid-dynamics equations proposed for the purpose and applied under semi-solid conditions:

$$T_{out} = \frac{\rho V c T_{in} - Q}{\rho V c} \quad (3)$$

$$T_{out} = \frac{Q + \rho V c T_{in}}{\rho V c} \quad (4)$$

In particular eq. (3) describes the temperature decrease with given Q heat and (4) the temperature increase for obtained Q heat where T_{in} represents the initial temperature of the considered layer and the T_{out} the temperature of the layer after Q heat exchanging.

The models were applied at the layers at 215°C. Lower Q values are obtained for the condition at 150°C. These values were considered under vacuum cooling.

The model for the description of the power heat exchanged under artificial cooling that is with calm air action is:

$$q = \bar{h} A \Delta T \quad (5)$$

q= power exchanged (W)
$\bar{h}$= convective heat exchange coefficient
A= contact area

The additional heat exchanged to be considered in the eqs. (3) and (4) under calm air condition can be reported as follows:

$$Q_{air} = q \cdot \Delta t \quad (6)$$

The decreasing temperature determines a interlayer length variation, due the layer to layer temperature gradient, and a related surface load described with the equations:

$$l_i = l \cdot \kappa \cdot \Delta T \quad (7)$$

$$L = \sum_{i=1}^{N} G \cdot h^{-1} \cdot l_i \cdot A_i \quad (8)$$

where:

l= nominal length
l_i=elongation of each element *i* in which the entire length *l* can be subdivided
k=thermal dilatation coefficient
L= surface load
G= tangential modulus at temperature over 70°C
h= layer thickness
A_i=Interlayer contact surface of each element *i* in which the entire surface A can be subdivided
ΔT= temperature difference between layers
N= number of elements i composing the layer.

In order to understand the thermal behaviour of the whole model the numerical simulation based on finite element analysis was performed. The characteristics of the numerical model were represented by a hollow half of the model realized in layers about 10 times bigger than real to evidence the phenomenon. The adaptive mesh was adopted with thermophysical characteristics of the material under investigation. The loaded layer was set at 215 °C with the previous one set some degrees lower to consider the decrease in temperature between applying two layers. The first deposited layer on the basis of Figure 5, that represents the building direction in the STL system, was considered at 18°C. The conductive heat exchange per time unit was obtained by the contact between subsequent layers. The temperature decrease along the model is reported at next paragraph. At the same time the volume variation was provided by simulation and warpage amount obtained and shown at the next together with the study of a further condition at 150°C.

Results

The results in terms of the investigations on the physical model are able to demonstrate that a too much rough arc determines a curved surface not respecting the requirements of a typical smooth geometry for ergonomic or assembly purposes. When the connection angle between the planar and curved surface is equal to 90° the obtained physical model is reported in Fig. 6 in which continuity solutions appear. In detail, on the left of the model the difficult in realizing the connection between the curved and the planar parts without any support can be observed being the same the building direction.

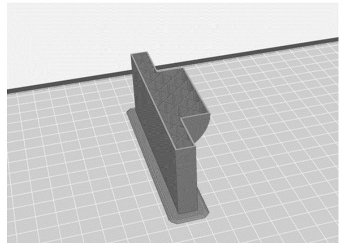


Figure 5. Slicing of the STL for building purposes perpendicular to building direction.

Under the conditions of the present investigation the problem cannot be solved varying process parameters that are extruder velocity, calm air action and of course deposition strategy. The solution is better represented by the realization of a physical model with a connection angle of about 70° as reported in Fig. 7 after different trials. While the discretization of the arc is reduced in the CAD environment by improvement in tolerances and adopting a different sketching strategy characterized by an elevate number of reference points along the arc. The whole result is reported in Fig. 8 in which the realized manufact can match the already described purposes. Even if some slight problems remain due to the volume variation during deposition of the layers producing possible warpage, distortion and tensioning between layers. These behaviours of the PLA blend polymer under investigation can be explained as follows. The temperature values along the model of Fig. 5 representing the building direction in the STL environment can be described by a thermal gradient.

During experiments two different conditions are considered. One of them represents the temperature of the deposited layer at the contact with the previous being the temperature of the extruder on average 25°C higher than the deposited one. The first condition at 215° C and the second at 150°C were analyzed. Under those two conditions the temperature behaviour of two subsequent layers is described with eqs. (1) and (2) resulting in the diagram given in Fig. 9 in which the higher temperature of the last layer tends to follow the decrease in temperature of the previous layer being the latter already very close to the environment temperature. The high absolute slope can be explained with the low volumes of the layers that means low thermal capacity of the zone considered in the investigation and high thermal capacity imposed for the other previously already realized part of the model.

By the numerical simulation the obtained thermal flow at the condition of 215 °C is of 0.145 W between layers. When the models (3) and (4) are considered the decrease in temperature of the last layer is described in the same Fig. 9a). As well as the increase in temperature of the previous layer due to the heat exchanging at 0 m/s air flow, that is without considering the calm air condition.

When the air flow of 0.7-0.8 m/s (artificial cooling) representing the upper values under the calm air condition an additional thermal flow q of 0.700 W needs to be considered by eq. (5). The subsequent Q air obtained by the eq. (6) and added to eqs. (3) and (4) allows the obtaining of the results reported in Fig. 9a).

That means a faster decrease in temperature of both the last and the previous layers described in the graphs by the eqs. (3) and (6) and by eqs. (4) and (6). When considering those, the situation is described by the last layer deposition at 215°C over a previous layer at 140°C resulting from the artificial cooling after few seconds. The results shown by the simulation are reported for that condition in Fig. 10 where the difference between 0 m/s and 0.7-0.8 m/s air flow can be observed. In Fig. 11 the simulation shows the temperature gradient at the connection between the planar part and the dome. In the same figure the difference in temperature between the under deposition layer and the other can be observed. The condition at 150° is shown in Fig. 9b).

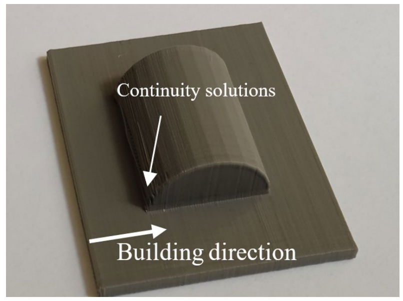


Figure 6. Physical model by FDM with a rough arc and connection angle of 90°.

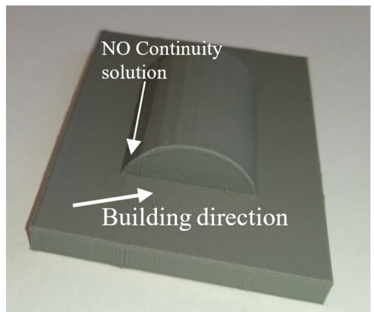


Figure 7. Physical model obtained by FDM with a rough arc and connection angle of 70°.

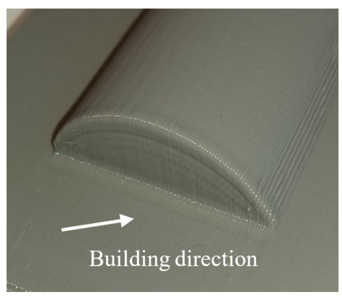
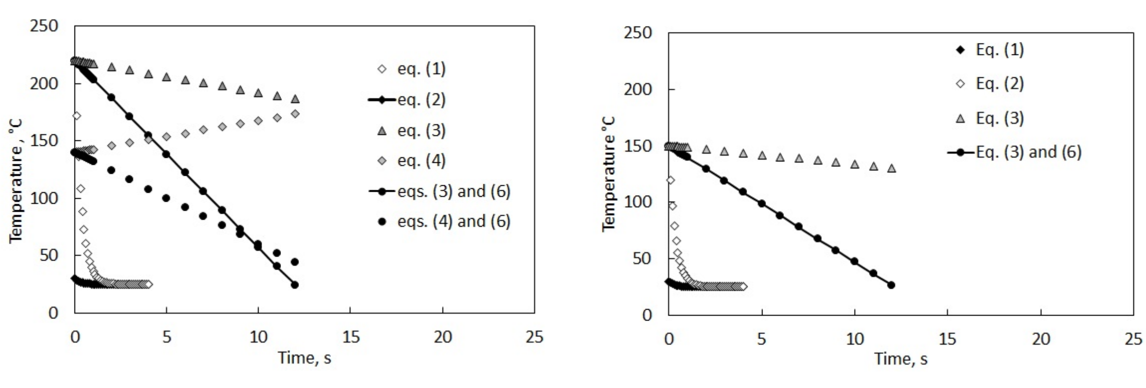
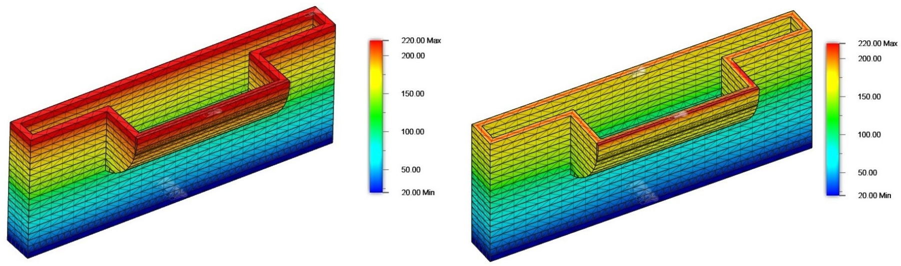


Figure 8. Physical model obtained by FDM with the finest arc and connection angle of 70°.



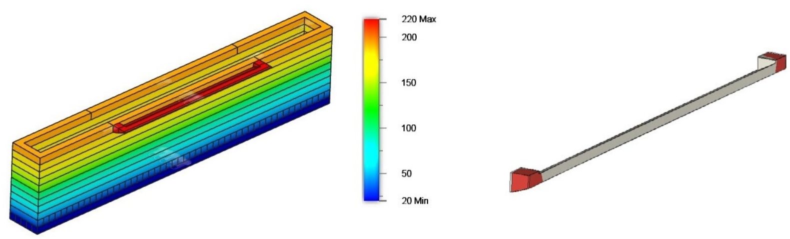
a) b)

Figure 9. Thermal modeling of the layer deposition without artificial cooling and with artificial cooling at 215°C (a) and at 150°C (b).



a) b)

Figure 10. Thermal modeling of the layer deposition without artificial cooling (a) and with artificial cooling (b) at 215°C condition.



a) b)

Figure 11. Thermal simulation of the deposition of the layer at the connection and subsequent length variation.

The deformation occurring between layers obtained using length values given by eq. 7 makes possible the calculation of the mean tangential stress using values given by eq. 8 divided by the layer area. A tangential stress of approximatively 45 MPa for a initial temperature difference of 215-140 °C and of about 9 MPa for higher velocity of the extruder, that means lower temperature interval, can be calculated. Such results are obtained on a layer thickness of 0.2 mm over a length of 100 mm of the planar part. When the temperature interval further increases the tangential stress is increased and difficult to subsliding with possible detachments between layers. All of that influences the surface quality of the object with deformation and/or relative rigid movements of the different realized parts of the component.

A similar situation can produce subsliding and distortion at the connection between the planar parts and the curved ones of the object. That is, the connection of the vertical planar part of the dome of Fig. 3 and the connection of 70° between the planar basis and the curved part of Fig. 4. This type of behaviours reported and evidenced by Fig. 10 and Fig. 11 determines the slight lack of geometrical requirements respect along the arc being the whole shrinkage in that zone of about 0.15 - 0.18 mm. Such critical zones can be visible in previous figures where the PLA blend FDM realized objects can be observed.

In general, low temperatures and a discretized digital information determine higher real layer thickness and lower shrinkage with reduced plastic tension states phenomena, but a very rough description of the geometry when compared with the finest one. In other words, under the condition of the scientific investigation, high temperatures and a correctly discretized STL determine low layer thickness and smooth surfaces. The risk of warpage and lack of precision on the arc and at the connection between the planar part and the curved is strictly depending on the air cooling condition simulating the waiting time between layers at given extrusion velocity. Such results are similar to those found by other authors on PLA and different polymer materials [1,5,8,10, 14-15].

Summary

The present investigation aimed at applying the proposed methodology in which the digital information and the numerical simulation of a model characterized by a planar part connected with a semicylinder are used in conjunction with analytical modeling for temperature distribution and interlayer behaviour studying. The objective was the realization of a physical PLA blend model avoiding supporting and related surficial treatments.

It was found that the connection angle between the dome and planar part represents the key variable to realize a physical model with a building direction able to avoid supports and subsequent treatments in such zones.

By analytical modeling the temperature description of two subsequent layers was made considering the artificial and vacuum cooling being the latter in air flow characterized by 0 m/s. By increasing the air flow up to 0.7-0.8 m/s, a decrease in the temperature of both of the subsequent layers can be effectively realized. By an initial difference between the temperature layers of about 60-70 °C being the last one at 215°C the effect at the interlayer surface was a analytically calculated tension of about 45 MPa being still after few seconds in the plastic region at those temperatures. Such conditions were responsible for the volume variation and warpage in particular at the connections between the planar and curved parts.

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