International Journal of Mechanical Engineering and Robotics Research Vol. 10, No. 6, June 2021

Computer Aided Definition of the Printing Conditions of Parts Made by FFF

Sidonie F. Costa
CIICESI, Escola Superior de Tecnologia e Gestão, Politécnico do Porto, Felgueiras, Portugal
e-mail: sfc@estg.ipp.pt

Fernando M. Duarte and José A. Covas
Institute for Polymers and Composites (IPC), Department of Polymer Engineering, University of Minho, Guimarães, Portugal
e-mail:{fduarte, jcovas}@dep.uminho.pt

***Abstract*—The growing worldwide use of 3D printing techniques requires the support of scientific research to improve the process and the quality of 3D printed parts. In a previous work, the authors developed a computer code that predicts the temperature evolution and the adhesion at any location of a 3D part produced by Fused Filament Fabrication (FFF). Here, a 3D printed scalpel handle is used as a case study to evaluate the usefulness of the simulation tool in the definition of the printing conditions. Considering a printer with a convection oven, the best built orientation is selected. The results demonstrate the complexity of the heat transfer mechanisms that develop during the deposition stage. For this particular case study, the importance of using a 3D printer fitted with a convection oven is demonstrated, as its positive effect on adhesion cannot be compensated by tuning other process parameters.**

***Index Terms*—3D printing, fused filament fabrication, modelling, heat transfer, adhesion**

I. INTRODUCTION

Fused Filament Fabrication (FFF) refers to the process of creating 3D objects from a Computer-Aided Design (CAD) model through the sequential deposition of horizontal layers, each composed of extruded filaments. In contrast with traditional manufacturing techniques, this process allows the fabrication of products with complex geometries without using a mold, and with a significant reduction in costs and human intervention [1], [2]. Moreover, FFF can produce prototypes to validate their properties before the implementation phase, which maximizes quality, competitiveness and reduce the production cycle time [3]. Polymer materials are used more frequently, but ceramics and metals can also be processed, thus increasing the usefulness of the technique [4].

FFF is being adopted in many sectors, including aerospace, automotive, electronic and health industries, and also in architecture, for the production of prototypes or of final parts. The medical field is particularly important [5]-[7], e.g., for printing implants and prostheses, bioprinting tissues and organs, anatomical models for surgical preparation and surgical instruments.

Despite of its apparent simplicity, FFF comprises a large of parameters that determine the quality and reliability of the printed parts. Also, the variety of geometries that can be manufactured creates difficulties in establishing general design and manufacture guidelines to obtain good quality parts. It has been widely demonstrated that 3D printed parts often show poor quality with respect to surface finish, dimensional accuracy and mechanical resistance [8]-[10]. The latter is generally attributed to insufficient bonding between adjacent filaments, which in turn results from the variation of their temperature during deposition and cooling [11], [12]. Indeed, as illustrated in Fig. 1, when a new filament is deposited, bonding with an adjacent filament is influenced by their temperatures and time during which the viscosities remain adequate for the necessary molecular interdiffusion. These local conditions are created by the thermal environment created during cooling, which depends on extrusion velocity and temperature, environment temperature, filament dimensions, part geometry, deposition strategy, heat transfer coefficients, etc.

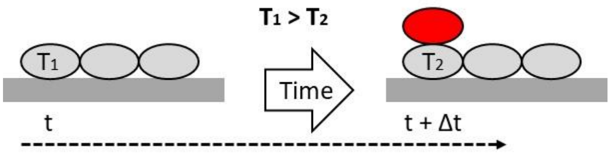


Figure 1. Contact between filaments during deposition.

Therefore, the availability of mathematical models that can predict spatial and temporal temperature fields and adhesion, considering all relevant process parameters, is very useful. As the result of previous research, the authors developed such a model [13], by activating whenever relevant (i.e, depending on the part geometry and deposition strategy) the physical contacts between any filament and its neighbors during the printing stage.

Manuscript received December 21, 2020; revised May 7, 2021.

doi: 10.18178/ijmerr.10.6.301-307

This work aims at using the available predictive model to set the adequate printing conditions of parts to be manufactured by FFF, while demonstrating the effect of selected process parameters on part quality, here measured as adhesion between filaments.

II. PREDICTIVE FFF MODEL

During the deposition stage of FFF, multiple heat transfer phenomena develop, including conduction heat transfer within the filament, both lengthwise and crosswise, convection and radiation heat transfer with the surroundings, and conduction heat transfer with adjacent filaments and with the support. It was demonstrated that cooling of the filaments relies mostly on heat transfer with the support, with the environment, and with adjacent filaments [14]. The corresponding simplified energy equation can thus be written and solved analytically using the characteristic polynomial method [15]. This solution is used by an algorithm that automatically defines and up-dates contacts. A healing criterion is then applied to assess whether bonding develop for all pairs of adjacent filaments [16]. A MatLab® computer code was implemented and its predictions were generally in good agreement with the experimental data [13]. The corresponding general flowchart is depicted in Fig. 2.

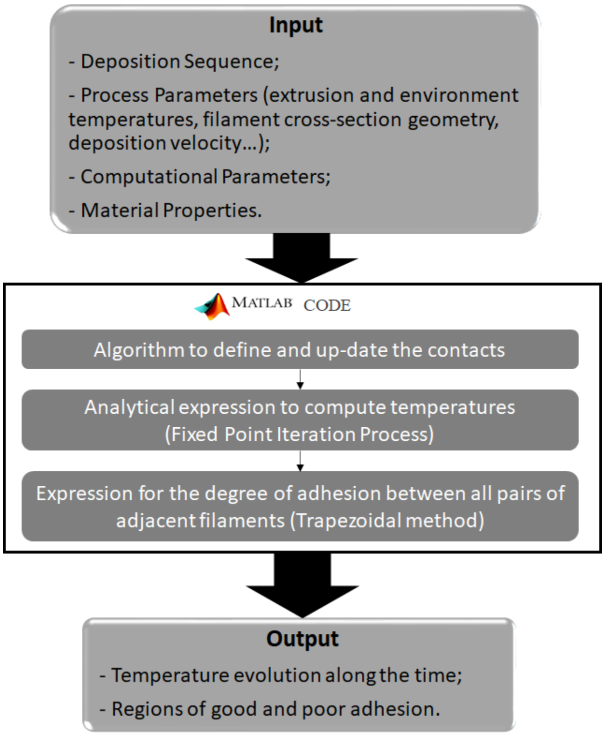


Figure 2. General flowchart of the computer code.

The computer code can take in two materials (material for the part and support), as well as different building strategies and build orientations. Build orientation refers to the rotation of the part in the manufacturing space around the axes of the machine's coordinate system [17]. Its importance to surface quality, geometric accuracy, mechanical properties, and part cost are well documented [18]-[21].

Therefore, the code can be used to define the set of operating conditions that assure the manufacture/printing of a good quality part. Quality is measured here as the percentage of volume of the part in which adhesion/bonding between adjacent filaments has been achieved. Fig. 3 presents the flowchart of the proposed methodology. Considering a printer with a convection oven, the best built orientation is selected based on the temperature predictions. Then, the extrusion temperature window assuring good adhesion is defined. An attempt to balance the heat losses by changing relevant processing parameters (extrusion temperature, extrusion velocity and support temperature) is then performed.

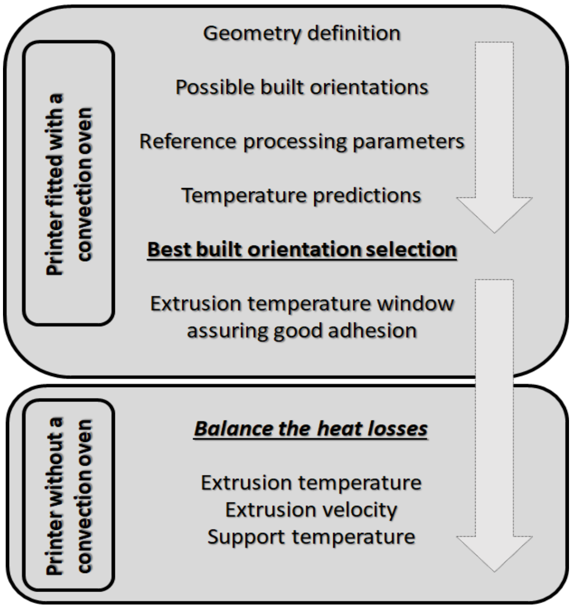


Figure 3. Flowchart of the proposed methodology.

III. CASE STUDY

A. *Part Geometry and Material*

3D printing is advantageous for the manufacture of surgical instruments, due to the inherent geometrical freedom of the parts, easy adaptation of the geometry to specific needs, and significantly lower production costs [22]. In addition, it poses a solution to overcome logistical challenges of providing sterile instruments, as in space missions [23]. Despite the potential benefits, studies of 3D printing of surgical instruments are scarce. Kondor et al. [24] printed a basic surgical kit that was successfully used to perform a laparotomy procedure on a training simulator. Subsequently, Rankin et al. printed an army/navy surgical retractor and concluded that the instrument had the mechanical resistance required in an operating room [25]. A simple scalpel handle was selected for this study (see Fig. 4), to be manufactured in Acrylonitrile butadiene styrene (ABS) polymer, with the properties shown in Table I.

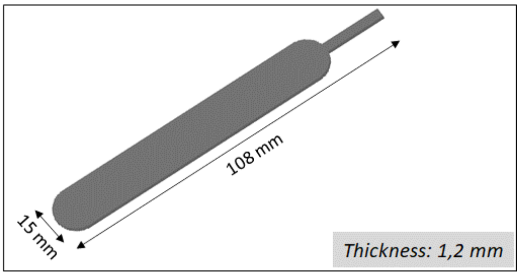


Figure 4. Geometry of the scalpel handle.

TABLE I. MATERIAL PROPERTIES

Property	**ABS P400**
Density, ρ (kg/m^3)	1050
Thermal conductivity, k (W/m. ℃)	0.18
Specific heat, C (J/kg. ℃)	2020

B. Process and Computational Parameters

Table II presents reference process parameters (and the values for the various heat transfer coefficients) on the basis of previous knowledge of the process, while Table III contains the computational parameters.

The part will be built using unidirectional and aligned filaments. Under these conditions, it will take approximately 12 minutes and 5 seconds to print the handle. The corresponding thermal and adhesion computations will require around 3.5 hours (HTC/HPC cluster with dual Intel Xeon processor), which demonstrates the complexity of the heat transfer problem and the large number of thermal conditions that must be considered.

TABLE II. REFERENCE PROCESS PARAMETERS AND HEAT TRANSFER COEFFICIENTS

Property	**Value**
Extrusion Temperature, T_L (℃)	270
Environment Temperature, T_E (℃)	70
Support Temperature, T_{sup} (℃)	70
Extrusion Velocity, v (m/s)	0.025
Convective heat transfer coefficient, h_{conv} (W/m^2. ℃)	65
Thermal contact conductance between adjacent filaments, h_i (W/m^2. ℃)	$h_i \in [10^{-4}; 220]$
Thermal contact conductance between filaments and support, h_{sup} (W/m^2. ℃)	10
Fraction of perimeter in contact with another filament or with support, λ_i	0.25
Filament cross-section width, w (mm)	0.03
Filament cross-section height, h (mm)	0.03

TABLE III. COMPUTATIONAL PARAMETERS

Property	**Value**
Time increment, t_i (s)	0.012
Temperature convergence error, ε (℃)	1

C. Build Orientations

As illustrated in Fig. 5, only two build orientations are feasible due to the geometry and thickness of the part. In this case, the built orientation does not change the part volume (i.e., no need of support material), or the contact area with the support. Still, it will affect the instants at which contacts arise. Given the handle geometry, the two build orientations will create filament lengths ranging between 78 and 110 mm (orientation 1) and between 3 and 15 mm (orientation 2). Consequently, at the same extrusion velocity, time periods are approximately thirty times lower for orientation 2.

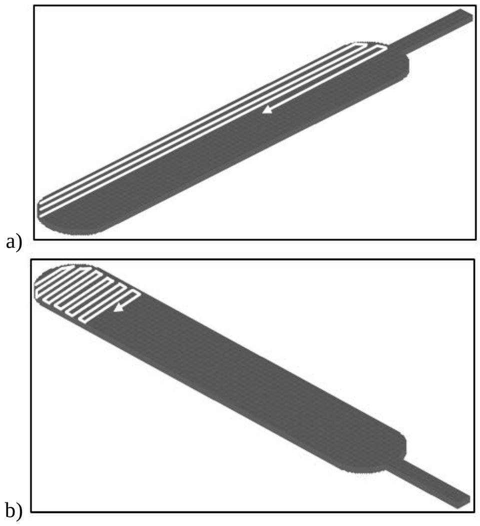
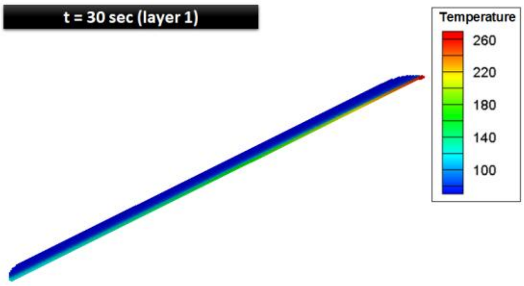


Figure 5. Build orientations for the scalpel handle; a) orientation 1 (4 layers, 200 filaments); b) orientation 2 (4 layers, 1440 filaments).

IV. RESULTS AND DISCUSSION

A. Temperature Evolution

The evolution of temperature with time/deposition (at specific times) for orientations 1 and 2 can be observed in Fig. 6 and Fig. 7, respectively. Due to their small diameter (0.3 mm), the filaments cool down quickly, despite the low thermal conductivity of ABS. It can also be seen that every time a new hotter filament is deposited, the previous ones that become into contact with it reheat. This effect is more important for orientation 2, where thermal contacts between adjacent filament segments occur more frequently because the lengths of the filaments are considerably lower. In principle, re-heating favors the development of good adhesion and henceforth of a better mechanical performance. Consequently, based on these temperature predictions, build orientation 2 seems preferable.



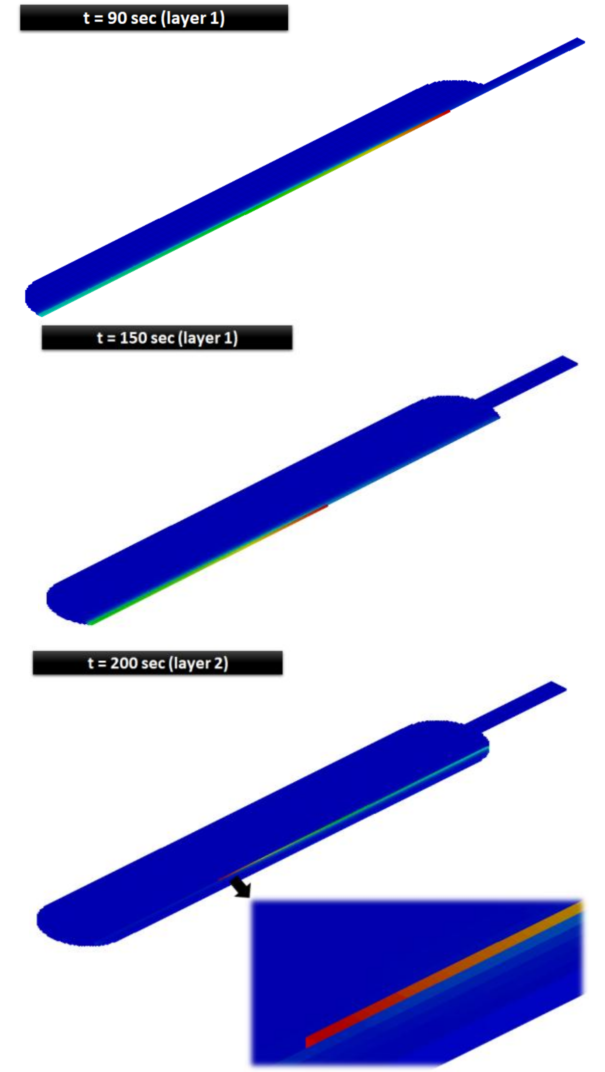
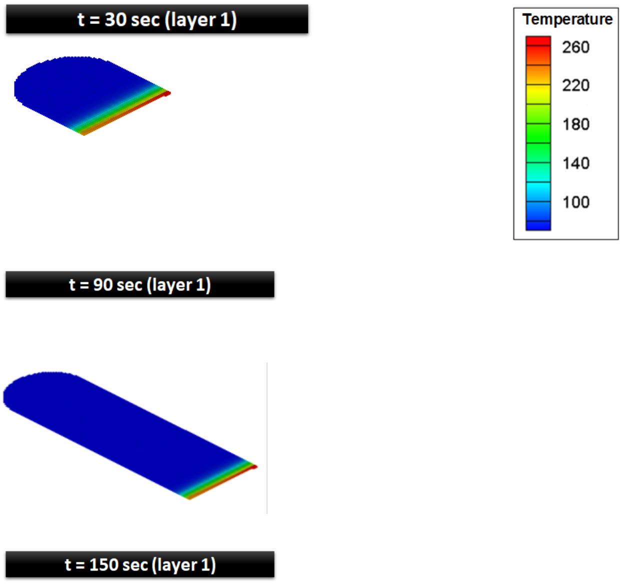


Figure 6. Temperatures at the times indicated of the deposition process for orientation 1 (1^{st} and 2^{nd} layers).



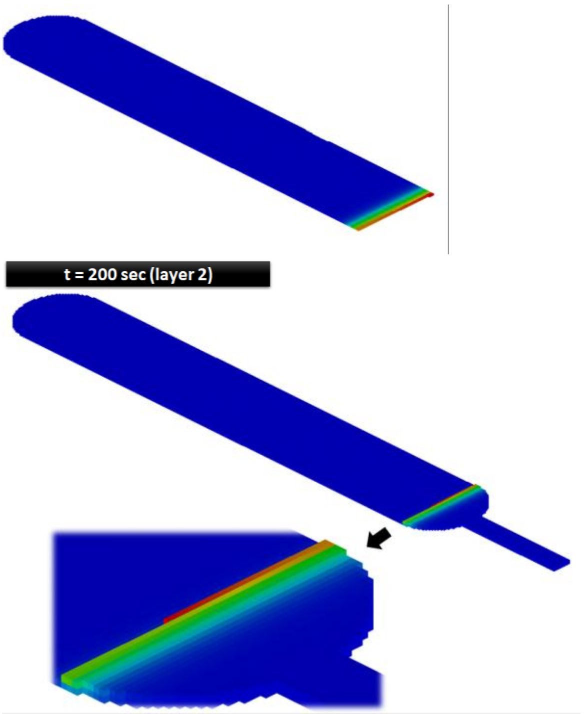


Figure 7. Temperatures at the times indicated of the deposition process for orientation 2 (1^{st} and 2^{nd} layers).

B. Adhesion

Once the build orientation is selected, it is possible to determine the extrusion temperature window assuring good adhesion. The lower this temperature, the lower the power consumption and the faster the production cycle. Fig. 8 predicts the percentage of the volume of the part exhibiting good adhesion, for a range of extrusion temperatures from 245 to 270 ℃. For the sake of comparison, data are presented for the two build orientations.

Below 260 ℃, regardless of the build orientation adopted, parts will exhibit poor mechanical performance, as the filaments do not adhere to each other. If the extrusion temperature is raised to 270 ℃, the problem is solved. Interestingly, this is the extrusion temperature that most 3D printers adopt when processing ABS. As expected, build orientation 2 is preferable, as good parts are already obtained at 265 ℃.

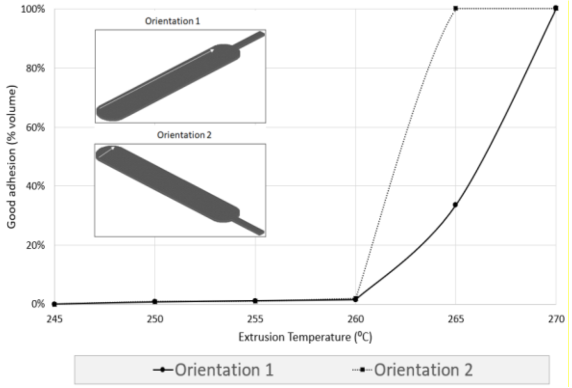


Figure 8. Good adhesion volume fraction vs. extrusion temperature for the two build orientations.

The above calculations were made considering that the 3D printer is fitted with a convection oven with controlled temperature (kept at 70 ℃). However, many of the most popular 3D printers operate at room temperature. Thus, build orientation 2 was assumed and the regions of poor and good adhesion were computed considering the environment and the support temperature $T_E = T_{sup} = 25$ ℃ and natural convection, $h_{conv} = 30$ W/m^2. ℃. As seen in Fig. 9.a), this results in a handle with poor quality (with only 1% of the volume having reached good filament bonding). Even if the process is balanced by raising the extrusion temperature up to 300 ℃, little improvement is achieved (Fig. 9.b)). Fig. 9 reveals that the regions where good adhesion is assured are those at the narrower edge. This was anticipated, since in this zone the filaments are shorter and therefore they contact each other more frequently.

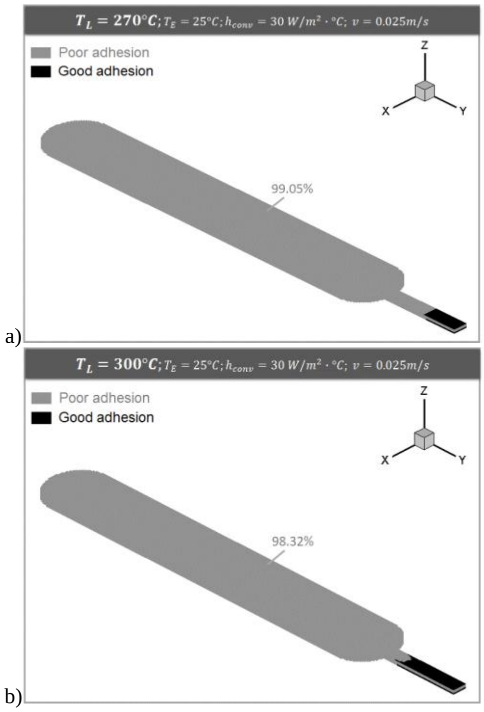


Figure 9. Adhesion mapping for build orientation 2 with uncontrolled environment, extrusion velocity of 0.025m/s, extrusion temperature: a) 270 ℃; b) 300 ℃.

Another strategy to balance the heat losses to the environment would be to increase the extrusion velocity, as this would reduce the time-period between contacts. The adhesion maps displayed in Fig. 10 demonstrate that this route was only partially successful for the part under study. When duplicating the extrusion velocity from 0.025m/s to 0.05m/s, the percentage of the part with poor adhesion remains very high when the filament is extruded at 270 ℃ (Fig. 10a)), and decreases to 68% if extrusion is performed at 300 ℃ (Fig. 10b)). In this last case, the regions with poor adhesion are located on the first layer due to the contact with support and on the last layer since the heat losses with environment are more considerable.

In practice, an intermediate strategy is usually adopted, i.e., since no convection oven is available, the environment temperature remains uncontrolled, but the support is heated (Fig. 11).

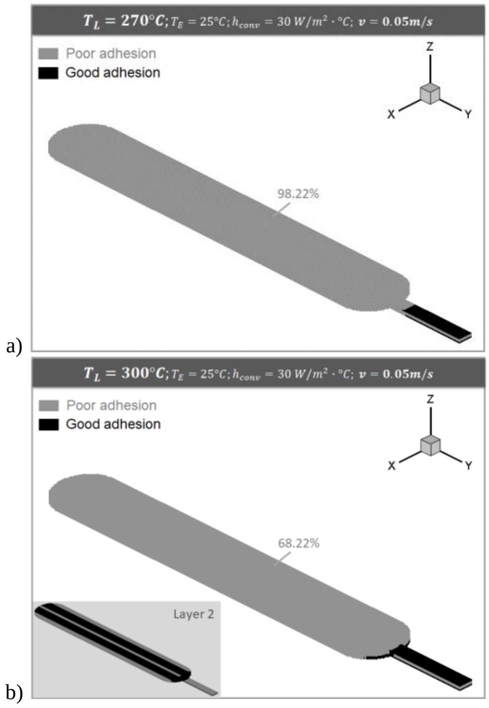


Figure 10. Adhesion mapping for build orientation 2 with uncontrolled environment, extrusion velocity of 0.05m/s, extrusion temperature: a) 270 ℃; b) 300 ℃.

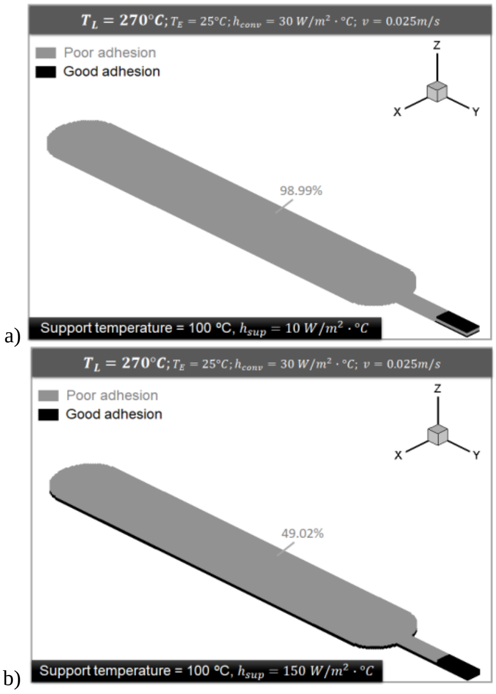


Figure 11. Adhesion mapping for build orientation 2 with uncontrolled environment, extrusion velocity of 0.025m/s, support temperature T_{sup} = 100 ℃: a) h_{sup} = 10 W/m^2. ℃; b) h_{sup} = 150 W/m^2. ℃.

Fig. 11 presents the results of computations performed assuming that the support is kept at T_{sup} = 100 ℃, for two values of the thermal contact conductance. The data obtained is not too different from that shown in Fig. 10 for the effect of extrusion temperature. The unique distinction is related with the location of the regions where good adhesion is assured, that is, on layers 1 and 2 due to the proximity of support. Keeping the extrusion temperature at 270 ℃, without using a convection oven, but heating the support to 100 ℃ and assuming a good thermal conductance, it is possible to assure that approximately half of the part exhibits good adhesion.

V. CONCLUSIONS

The results discussed in this work demonstrate the complexity of the heat transfer mechanisms that develop during the deposition stage of Fused Filament Fabrication (FFF), one of the most popular 3D printing techniques. They also demonstrate how accurate process modelling can be used not only to better understand the effect of the process parameters and part geometry on the resulting bonding between the filaments, but also to assist practical the definition of adequate operating conditions.

In the case of a simple scalpel handle, which has a flat long, narrow and thin geometry, it is important to use a 3D printer fitted with a convection oven, as its positive effect on adhesion cannot be compensated by tuning other process parameters such as extrusion temperature and velocity.

In a future work, other specific geometries will be studied to conclude about the adequate strategies that will improve the final quality, as well as define the best conditions to optimize the process. Moreover, some guidelines that relate geometrical features and quality of adhesion can be deduced.

ACKNOWLEDGMENTS

This work has been partially supported by national funds through FCT – Fundação para a Ciência e Tecnologia through project UIDB/04728/2020.

Partial support for this research has been provided by the Search-ON2: Revitalization of HPC infrastructure of Uminho, (NORTE-07-0162-FEDER-000086), co-funded by the North Portugal Regional Operational Programme (ON.2-O Novo Norte), under the National Strategic Reference Framework (NSRF), through the European Regional Development Fund (ERDF), at the University of Minho, Portugal.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All co-authors designed the research and discussed the results. Sidonie F. Costa selected the case study, performed the computations and wrote a first draft of the manuscript. Fernando M. Duarte and José A. Covas contributed to the final manuscript.

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Sidonie F. Costa was born on April 30, 1982 in Mont Saint Aignan, France. He is living in Portugal since 2000, she received her degree in mathematics teaching from University of Minho, Braga, Portugal, in 2005, her specialization in mathematics and mechanical applications in 2006 and her PhD in polymer and composite science and engineering in 2013, from the University of Minho, Guimarães, Portugal. Since 2010, she is an adjunct professor in the Department of Exact Sciences of the School of Management and Technology (ESTG), Porto Polytechnic Institute (P.PORTO), Felgueiras, Portugal, and is currently an integrated member of the Center for Innovation and Research in Business Sciences and Information Systems (CIICESI), ESTG, P.PORTO, Felgueiras, Portugal. Her experience includes the mathematical modeling of engineering problems, particularly in the area of rapid prototyping, as evidenced by some international conference participations and publications in this area. In parallel, she created the project "b-Mat@plicada" at the ESTG, a b-Learning course consisting of several educational videos on mathematical topics to assist students in their study.

Fernando M. Duarte is an assistant professor in the Department of Polymer Engineering at the University of Minho (UM). He graduated in production engineering - plastics from UM in February 1992 and received a PhD in science and polymer engineering from University of Minho, Portugal, in October 2003. He develops research activities at the Institute of Polymers and Composites Research Unit, IPC, in thermoforming, fused filament fabrication, FFF, and in the development and characterization of degradable, biodegradable polymer materials and nanocomposites. He was part of the research team of several national research projects and has published / accepted for publication more than 25 articles in international journals with arbitration and more than 40 communications in international and national conference proceedings. It also develops R&D activities and the transfer of expertise and technology with the industry, namely through the Pole of Innovation in Polymer Engineering (PIEP), having participated in around 20 cooperation / research projects between University and Industry.

José A. Covas is full professor at the Department of Polymer Engineering of the University of Minho (UM), Portugal, since 1998, having joined this institution in 1979. His PhD thesis received the E Gaspar Award in 1985 by the Institute of Materials, UK. His scientific interests focus on polymer processing (in-process monitoring, optimization, technological development), compounding (manufacture of polymer blends and nanocomposites) and additive manufacturing. He has authored over 200 scientific papers in peer-reviewed international journals, books and book chapters, as well as 11 patents (one of which was awarded a gold medal at the 47th International Patents Exhibition, Genève, 2019). He coordinated the European Master EURHEO EMMC - European Masters in Engineering Rheology. He is the editor-in-chief of the International Polymer Processing Journal, associate editor of the Polímeros journal (Brazil) and member of the editorial board of five other international scientific journals. He is an expert / evaluator for ten funding agencies (ranked top 6% by EPSRC, UK) in Europe and Canada and for the European Research Council. He is a member of the executive committee of the Polymer Processing Society. He is vice president of PIEP (Pole of Innovation in Polymer Engineering), a private association for industrially oriented R&D. He has maintained intensive collaboration with industry, including some of Europe's leading raw material manufacturers, as well as with ESA (European Space Agency) and CERN.