

Protocols for 3D-printing pieces by fused deposition modelling for research purposes: from modeling to post-printing treatment

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Abstract

Additive manufacturing or 3D-printing is a revolutionary technique for prototyping and building objects for final use. Since the first registers at ~1890 the improved technology has boosted the applications of such technique, decreasing its market price. The most affordable 3D-print technique is Fuse Deposition Modeling (FDM), which is based on a layer-by-layer deposition of a fused polymer on a cooled table. Although FDM has been used by industrials, students and researchers, there are few published protocols dealing with small challenges and daily problems. Here we use a basic object to detail pre- and post-printing steps. This technical note offers the reader tools to model, print and treat the 3D-object. We point out basic challenges, such as positioning the objects on the virtual table of the slicing software, that may lead towards undesirable printed pieces. The protocols described here do not cover the uncountable possibilities of 3D-printing by FDM, but surely help researchers and industrials to start working with it.

Keywords: Fused deposition modeling, Basic protocol, pre-printing, Post-printing, 3D-printing.

1. Introduction

3D-printing or additive manufacturing is an emerging and highly useful technique for prototyping. This revolutionary technique allows for the three-dimensional fabrication of any possible object, limited by its size and resolution in terms of details. 3D-printing is part of a set of technology, considered a third industrial revolution [1]. Compared to machining techniques, 3D-printing uses few amounts of materials and energy, which is economically feasible for even small industries and research laboratories with limited budget. This technology opens up the possibility of building complex objects with very low cost, which were only achieved by using sophisticated equipment [2,3].

The first registers of 3D-printing were reported by Joseph Blather in 1890. These reports show the use of a technique based on different levels to print topographic maps, lately replaced by papers. Since then, the technique has been improved and several methods have been developed [3]. Different machines are commercially available, with distinct operational hardware and based on a different method. Among the different methods, the most used are photopolymerization, powder-based, lamination and extrusion [3]. The extrusion method is the cheapest and simplest, so it is obviously the most commercialized technique, used for educational, industrial and research purposes. Herein we focus on this technique, following protocols, application and perspectives of its use.

The extrusion method, formally called Fused Deposition Modeling (FDM), was developed by Stratasys enterprise in 1992 [4]. FDM is based on a layer-by-layer deposition of a fused polymer on a cooled table, which is achieved by forcing the passage of a polymeric filament through a heated nozzle. The most common thermoplastic filament and their respective working temperatures are Polylactic Acid (PLA; 180-220 °C), Acrylonitrile Butadiene Styrene (ABS; 110-235 °C) and Polyethylene Terephthalate Glycol (PETG; 240-250 °C). Among those, ABS shows workability and mechanical resistance, PETG shows high-temperature stability and PLA shows chemical tolerance to some extent. The filaments are usually commercialized in diameters of 1.75 or 3.00 mm, depending on the diameter of the extrusion nozzle.

The versatility in use makes 3D-printing a useful tool to manufacture laboratory objects with (and without) improved physical-chemical characteristics,

specially to build devices applied in electroanalysis and applied electrochemistry [5–9]. Our group printed a US\$ 5 three-parts electrolyzer, which was used to convert glycerol into tartronate by using Pd nanocubes as catalyst [9]. Regarding 3D-printed plastics with improved properties, much effort has been spent in order to build conductive filaments, mainly by blending the polymer with a carbon material [7,10,11]. For instance, Rymansaib et al. developed a polystyrene/nanofiber filament containing graphite, which was used for analytical purposes [10]. Most recently, our group developed a method to turn an insulating plastic piece into conductive material by growing polyaniline on its surface, which allows further electrodeposition of any metal [9]. This protocol allows an industrial or researcher to indirectly 3D-print a metallic piece of any shape.

Although there are several groups and companies working on the FDM 3D-print technique, there are no protocols for users, but the user manuals that come with the machine. Any new user spends several hands-on hours to find solutions for simple daily problems, since modeling to post-printing treatment. Namely, the reproduction of a model is rarely trivial, since the pre- and post-treatments are rarely published. The user may find challenges as impossibilities to slice the desired piece, not intuitive software for modeling, unexpected printed object with excess of burrs, requiring finishing treatment and instability in different solvents. In this context, here we detail protocols for modeling, slicing and 3D-print an object by FDM. To illustrate the possible variables, we simulated printing a non-conventional, but simple piece.

2. Material and Methods

Here we illustrate the steps of FDM 3D-printing using a hollow box containing a screw thread. This model was chosen because it demonstrates different unexpected results that users may find, such as auxiliary printed-pieces for sustentation and lack of resolution for the screw. The piece was modeled by using Inventor® software and sliced in the Simplify 3D® software. It is worth mentioning that all procedures and features described are reproducible on any FDM based printer, as well as on any 3D modeling and slicing software. The experimental details of each step are discussed throughout the text.

3. Results and discussion

Several types of FDM-based 3D-printers are now available in the market. There are open and closed printers with x, y, and z motions that vary between the heater and the extruder nozzle. Despite the different models available, all 3D-printers based on the FDM method use the same operating principle. Therefore, we describe here the main operating parameters of a 3D-printer, from modeling to post-processing.

3.1. Nomenclature and parameters

Some parameters can be monitored even before starting the 3D-printing. These parameters are pivotal to evaluate the cost-effectiveness of the intent object. Most of the parameters are calculated by the slicing software (further discussed). The main parameters and nomenclatures are described in Table 1. The building time (BT) can be used to estimate the scale-up strategy of a piece and can also be used to evaluate the consumption of energy. The filament length (FL) and the plastic weight (PW) are imperative to estimate the autonomy of the filament, to calculate how many objects can be printed and what is the implication to the material cost (MC).

Table 1: Main parameters and nomenclatures provided by slicing software.

BT/min	FL/mm	PW/g	MC/US\$
Building Time	Filament Length	Plastic Weight	Material Cost

3.2. Modeling an object for 3D-printing

3D-printers have the same working set up than that found in conventional paper printers. The machine is connected to a computer via USB (or SB card), in order to interface the digital model to the printer. However, instead of printing in two-dimension, the additive manufacture machine prints object in deep, reaching x, y and z axes.

3.2.1 Modeling

In order to print the desired pieces, the modeling must be performed in a 3D modeling software (Figure 1), such as AUTO CAD®, Inventor®, Paint 3D®, among others. Additionally, there are devices that replace the modeling step by scanning the object. They are three-dimensional scanners and photo gravimetric equipment

that collect a set of images in several positions, allowing for the scanning of the object with accuracy. Whether the object is modeled from scratch or scanned, it must be finalized in .STL or .OBJ format to proceed with the next preprint step.

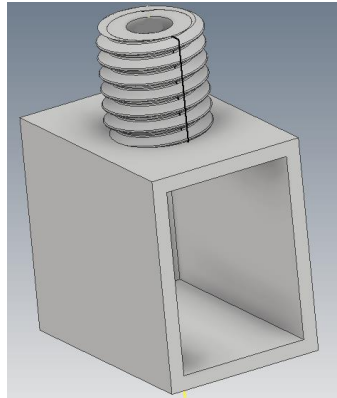


Figure 1: Representation of a hollow box modeled in 3D format.

Here we modeled a hollow box with a screw thread from scratch using Inventor®, as shown in Figure 1. The modeling of the hollow-box-part is simple. Firstly, one must build a rectangle in a 2D sketch, which must be extruded at the z axis direction to build a solid box. Next, a new rectangle must be drawn on one of the faces of the box and extruded at the inverse direction to build the hollow part. Finally, the screw is built by an Inventor® tool called Thread modeler.

3.2.2 Slicing

Once the object is modeled, another process is pivotal to enable 3D-printing, the piece must be "sliced". Slicing a piece means digitizing it in layered format, i.e. what was a single object now takes shape from one layer over another until the piece is finished. The format called ".Gcode" makes the file compatible, so the printer can follow the print commands. Finally, after obtaining the 3D model in a compatible format, it is necessary to plan the printing of the object, always considering economic factors of the chosen printing method.

Before slicing the piece, it is important to check the "printing profiles" provided by the supplier company. These profiles are ready-to-use algorithms that set the correct parameters, which are the temperature of the extrusion nozzle, the pace of heating and the temperature of the glass table. These profiles change for each filament (ABS, PLA, PETG, etc.) and for each resolution. It is also possible to choose the height of the deposition layer, which changes the final resolution of the object.

Simple and large objects do not require a high print resolution (layers of thin depositions) because the object does not show small well-defined details, since the layer size is indifferent to the resulting printed object. Therefore, the more detail the piece has, the higher the print resolution needs to be. The user may also customize new profiles, which is required in case a new composite filament with different melting point (and other properties) is produced.

3.3. 3D-printing through fused deposition modeling: An example

3.3.1 Preparing the printer

Prior to each print, it is necessary to apply a sticky product, such as glue, spray or liquid on the glass table (usually supplied by specialized stores in 3D-printing). This step is pivotal to fix the piece on the glass table and to avoid dragging during the printing. Moreover, the table is pre-heated to temperatures below the melting point of each filament in order to avoid thermal shrinkage of the piece [12].

3.3.2 Position of the piece on the glass platform

Besides the resolution of the piece, other important parameters to print high-quality objects are the time of printing and the way the piece is positioned on the platform (glass table). Figure 2 shows the screw box previously described (Figure 1) arranged in a slicing software, which simulates the piece in a 3D-printer.

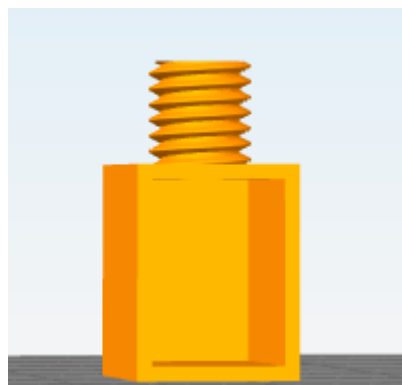


Figure 2: 3D-model designed in a slicing software.

When slicing the piece in the position of Figure 2, we realize from the simulation that the box will be completely obstructed by unnecessary internal burrs (see Figure 3-A), which are difficult to be polished after printing. On the other hand,

it can be minimized by simply changing the position of the piece. Figure 3-B shows the simulation of printing the piece in a lateral position, which avoids internal burrs.

It is important noticing that in both positions, there are no spaces between the pieces and the platform (Figures 3-A and 3-B). The line surrounding the piece (Figures 3-A and 3-B) indicates that the object is correctly positioned on the table. The absence of the surrounding line indicates that some part of the object is not perfectly aligned with the platform, and a manual adjustment is required through the x, y, and/or z axes in the slicing process.

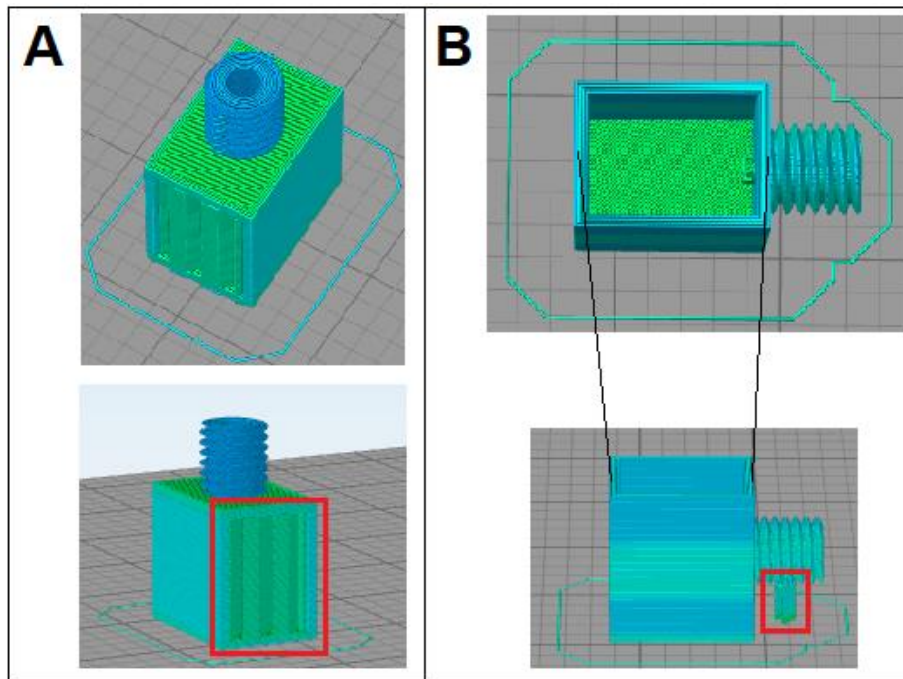


Figure 3: (A) Slicing of the box-bolt piece in the vertical position (B) horizontal position.

Whether the user prints a piece that is not fully in contact with the glass table, organized pillars will be built in order to sustain the object. Such additional burrs do not compromise the integrity of the final object; however, it increases the amount of post-printing treatment. This hypothesis is simulated and shown in Figure 4.

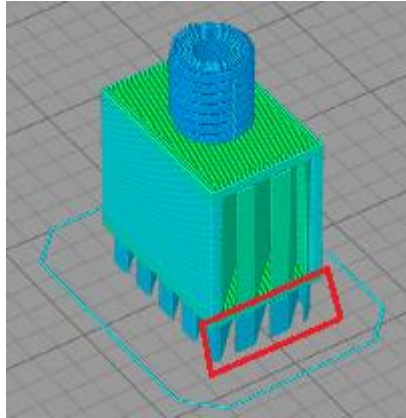


Figure 4: Piece incorrectly positioned on the glass platform, generating unnecessary burrs.

3.4. Post-printing treatment and chemical tolerance

3.4.1 Non-chemical post-treatment

The non-chemical treatment process concerns the mechanical removal of supporting pillars, burrs and polishing, which have no practical function to the utilization of the piece. This process is achieved by using mechanical tools, such as sandpaper, tweezers, scissors, and needles.

3.4.2 Chemical post-treatment

Depending on the purpose of the printed object (mainly for decorative purposes), the post-printing treatment process must be further improved, requiring the use of chemicals that refine the surface of the piece. Usually, chemical treatment is performed by using vapor of solvents, e.g. acetone, which slightly melts the surface of the piece, making it smoother and brighter.

It is necessary to choose carefully the solvent for the post-treatment. The choice must be made according to the tolerance of each thermoplastic material. Table 2 shows the tolerance of the main filaments used (PLA, PETG, and ABS) in some solvents.

Table 2: Examples of chemical tolerance of the main filaments used in FDM printing.

Material	Organochlorine	Acetone	1M H ₂ SO ₄	1 M NaOH
PLA	Low tolerance	Medium tolerance	High tolerance	High tolerance
PETG	Medium tolerance	High tolerance	High tolerance	High tolerance
ABS	Low tolerance	Low tolerance	High tolerance	High tolerance

If the thermoplastic exhibits a high tolerance to the reagent chosen for the post-treatment, the surface will not undergo any changes. If the thermoplastic has a low tolerance, the surface will quickly be modified, even deforming the object, since the control of solvent exposure becomes more difficult. Therefore, when choosing a solvent, it is ideal that the thermoplastic has medium tolerance at worst scenario, because the surface reaction can be controlled.

3.4.3 Perspectives of FDM printing in applied research

The FDM process is currently the most affordable 3D-printing method on the market. Companies such as Stratasy and 3DLAB, for example, are specialized in providing services from prototyping to services of software, maintenance, and materials support [13,14]. Such companies mediate the rapid development of the industry as they are specialized in developing, replacing and/or repairing objects demanded from major automotive, medical, dental, aerospace companies, among others.

In general, students and professionals who intend to work in the 3D-printing field should focus on both machine handling and 3D-design development by software such as AutoCAD®, Inventor®, 3D Max® and others. However, there is still a gap in the market concerning professionals who are specialized in 3D-modeling, as well as in printing and post-printing treatments.

4. Conclusion

Fused deposition modeling (FDM) is a widely spread technique for 3D-printing due to its low-cost and relatively easy handling. However, the increase in availability has overlapped the number of publications regarding the well-use of such technique. Therefore, it is hard to find useful and quick information regarding

fundamentals and protocols from modeling to post-printing treatments. In this technical note, we provided details about the FDM printing by using a basic object as example. The most important information is the influence of the position of the object on the glass table on the final piece, since burrs and pillars of sustentation may be found at the printed piece. We also simulated the printing in a slicing software to prove that non-chemical post-treatment may be minimized by simply changing the position of the piece.

We also showed that the wide use of this low-cost technology led to a lack of apt professionals. Hence, there is an impending need for documents to report special details and solution for daily problems in order to avoid wastes in terms of time and materials. This technical note opens up the alternative for users to follow the same strategy, and we encourage researchers to publish their protocols.

5. Bibliography

- [1] B. Roberts, *The Third Industrial Revolution: Implications for Planning Cities and Regions*, Work. Pap. Urban Front. 1 (2015).
- [2] S. Waheed, J.M. Cabot, N.P. Macdonald, T. Lewis, R.M. Guijt, B. Paull, M.C. Breadmore, 3D printed microfluidic devices: enablers and barriers, *Lab. Chip.* 16 (2016) 1993–2013. doi:10.1039/C6LC00284F.
- [3] A. Ambrosi, M. Pumera, 3D-printing technologies for electrochemical applications, *Chem. Soc. Rev.* 45 (2016) 2740–2755. doi:10.1039/C5CS00714C.
- [4] O.L. Editora, N.O.L. Editora, *Impressoras 3D - Guia Meu Próprio Negócio Especial Ideias Inovadoras Ed.04*, On Line Editora, 2016.
- [5] R. Bernasconi, G. Natale, M. Levi, L. Magagnin, Electroless Plating of PLA and PETG for 3D Printed Flexible Substrates, *ECS Trans.* 66 (2015) 23–35. doi:10.1149/06619.0023ecst.
- [6] C.L. Manzanares Palenzuela, F. Novotný, P. Krupička, Z. Sofer, M. Pumera, 3D-Printed Graphene/Poly(lactic Acid) Electrodes Promise High Sensitivity in Electroanalysis, *Anal. Chem.* 90 (2018) 5753–5757. doi:10.1021/acs.analchem.8b00083.
- [7] G.W. Bishop, J.E. Satterwhite, S. Bhakta, K. Kadimisetty, K.M. Gillette, E. Chen, J.F. Rusling, 3D-Printed Fluidic Devices for Nanoparticle Preparation and Flow-Injection Amperometry Using Integrated Prussian Blue Nanoparticle-Modified Electrodes, *Anal. Chem.* 87 (2015) 5437–5443. doi:10.1021/acs.analchem.5b00903.

- [8] K.-E. Guima, L.M. Alencar, G.C. da Silva, M.A.G. Trindade, C.A. Martins, 3D-printed electrolyzer for the conversion of glycerol into tartronate on Pd nanocubes, *ACS Sustain. Chem. Eng.* 6 (2017) 1202-1207. doi:10.1021/acssuschemeng.7b03490.
- [9] K.-E. Guima, V.H. R. Souza, C.A. Martins, Insulating 3D-printed templates are turned into metallic electrodes: application as electrodes for glycerol electrooxidation, *RSC Adv.* 9 (2019) 15158–15161. doi:10.1039/C9RA01436E.
- [10] Z. Rymansaib, P. Iravani, E. Emslie, M. Medvidović-Kosanović, M. Sak-Bosnar, R. Verdejo, F. Marken, All-Polystyrene 3D-Printed Electrochemical Device with Embedded Carbon Nanofiber-Graphite-Polystyrene Composite Conductor, *Electroanalysis.* 28 (2016) 1517–1523. doi:10.1002/elan.201600017.
- [11] A.S. Díaz-Marta, C.R. Tubío, C. Carbajales, C. Fernández, L. Escalante, E. Sotelo, F. Guitián, V.L. Barrio, A. Gil, A. Coelho, Three-Dimensional Printing in Catalysis: Combining 3D Heterogeneous Copper and Palladium Catalysts for Multicatalytic Multicomponent Reactions, *ACS Catal.* 8 (2018) 392–404. doi:10.1021/acscatal.7b02592.
- [12] M. Hofmann, 3D Printing Gets a Boost and Opportunities with Polymer Materials, *ACS Macro Lett.* 3 (2014) 382–386. doi:10.1021/mz4006556.
- [13] 3D Printing & Additive Manufacturing, *Stratasys.* (n.d.). <https://www.stratasys.com> (accessed August 4, 2019).
- [14] Impressão 3D Lab - Filamentos para impressora 3D e Soluções completas, *3dlab.* (n.d.). <https://3dlab.com.br/> (accessed August 4, 2019).