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# Generation of large scale robotic 3D printing trajectories and optimization of the quality of pieces

François Rosoux*, Henri Appeldoorn, Didier Garray, Eric Beeckman

Sirris, the collective centre of the Belgian technological industry, Seraing 4102, Belgium.

## Abstract

Incremental sheet forming is used to form metal sheets on massive dies. However, the waste and time lost due to the machining of dies can be a problem for both companies and the environment. Additive manufacturing is thus a potential alternative to classical machining of dies, but these complex geometries could be challenging for classical layer-by-layer 3D printing techniques. This paper will present an innovative process based on a 3D printing technology using 3-axis systems and a pellet extruder combined with the generation of non-planar trajectories in order to achieve good surface quality. PLA-based parts were realised to evaluate surface quality and mechanical properties. With such a technique, the obtained 3D printed parts were closer to the expected CAD geometries and smoother top surfaces were obtained. These improvements have been made possible through the development of specific post-processors and printing strategies in order to replicate the behaviour of a 3D printer at a larger scale, which is a current challenge in robotic 3D printing.

**Keywords:** 3D printing, non-planar, robotics, polymers, pellet extrusion

## 1. Introduction

Fused Deposition Modelling (FDM) 3D printing is a material extrusion technique using generally amorphous thermoplastic polymer filaments, heated and extruded through a nozzle. Common materials are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Alternative materials include ceramics or metals filled thermoplastics or gels. An extruder equipped with this nozzle can deposit material along its displacements and realize a piece layer-by-layer. This technique has been known since the 1990s and was introduced by Stratasys (Wohlers Associates, 2022).

The FDM process starts by converting a CAD file into an STL format. The file is then imported into slicing software to prepare the instructions for the 3D printer. Finally, the software outputs a G-code file readable by the 3D printer to print the parts (Singh & Davim, 2019).

FDM can use many types of materials and gives easy access to rapid prototyping. However, the surface finish, the weakness along Z axis, the anisotropic properties and the printing speed are among its drawbacks (Prakash et al., 2022).

In the frame of the incremental sheet forming (ISF) process, metal sheets are deformed against large dies. These are generally realized by machining and thus inducing considerable waste. When forming the sheets, some corrections of the dies are necessary to compensate for the springback effect for example. In that case, the successive transports of the die between the forming institute and the shop floor also negatively impacts the environment. For these reasons, an alternative would be to directly 3D print the die in the in-

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*Corresponding author: francois.rosoux@sirris.be

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cremental sheet forming machine. This technique has several benefits compared to the classical procedure, including limited waste production. Moreover, starting from polymer pellets as a raw material allows greater flexibility in terms of material choice. Thermoplastics pellets are also 10 times cheaper than filaments, and pellets extruders are now increasingly common on the market, such as those commercialized by CEAD and Titan Robotics (Wohlers Associates, 2022).

## Concept of non-planar 3D printing

Generally, pieces are realized by a succession of horizontal layers, inducing a stair-stepping aspect for the surfaces (Singh & Davim, 2019). In order to form metal sheets on dies with complex surfaces, this stair-stepping aspect could be detrimental for the quality of the final products. For this purpose, a very promising alternative is to develop non-planar 3D printing. This technique no longer prints successions of horizontal layers but rather real 3D surfaces on the top of the pieces. In this way, smoother parts can be obtained which is beneficial for ISF. However, non-planar 3D printing is still an underdeveloped concept and the associated software is seldom seen. Among the available solutions, the popular *Slic3r* has been modified in order to generate non-planar trajectories for FDM printers (Ahlers et al., 2019). Several studies using this solution have been summarized in the literature (O'Connell, 2021).

Among the other existing solutions, the first alternative to Slic3r is CurviSlicer. This solution consists in curving the planar layers by increasing or decreasing their thickness. It improves the surface quality at certain locations, but the stair-stepping aspect could not be avoided everywhere. As a result, the printing quality is only very slightly improved (Etienne et al., 2019).

Based on our own experience, another solution to achieve non-planar 3D printing is to use Rhino 6 Grasshopper. This is a modelling tool especially dedicated to create and modify complex shapes. With such tools, it is possible to cut a part into non-planar layers, but this approach is almost tailor-made for each part and is thus limited in terms of flexibility.

Another project at the research stage is the development of the 3, 4, and 5-axis slicer called Universal Slicing, allowing the printing of parts with any kind of layer or shape (Mueller, 2022).

In addition to the lack of appropriate existing slicers, most commercial FDM 3D printers are limited in terms of the admissible curvature in non-planar 3D printing. Indeed, very few of them have extruders with appropriate geometry to allow printing at a slope angle greater than a few degrees (O'Connell, 2021). One alternative is to mount an extruder on a robotic arm and benefit from the additional degrees of freedom and greater speed (Dave & Davim, 2021). The literature about non-planar 3D printing reports the use of a robotic 3D printer and the generation of complex trajectories with tailor-made solutions (Shembekar et al., 2019). Another paper (Mitropoulou, 2020) presents a methodology but it is only able to print single-wall pieces, the difficulty lying in synchronizing the extrusion commands with the robotic movements and to differentiate printing from travelling movements. Moreover, there is currently a large software limitation to the planning of paths and checking for collisions on a 5-axis machine.

Current alternatives to non-planar 3D printing in order to improve the surface quality of parts produced by FDM are very few in number (Dave & Davim, 2021; Singh & Davim, 2019). A first pre-processing solution is to perfectly tune the printing parameters in order to limit the defects. Post-processing of the part is also possible to improve its appearance. These techniques can be divided into 4 groups:

- Mechanical post-processing: use of sanding, abrasives to remove material excess.
- Chemical post-processing: finishing through the use of solvent vapor, painting.
- Thermal post-processing: laser-based processing, ironing.
- Hybrid post-processing: combination of additive and subtractive processes.

Another novel approach to improve the surface finish is based on ultrasound. This process is interesting because it does not cause a chemical reaction or corrode the parts. The technique was thus applied on ABS parts, realised by a FDM printer. The results showed that surface roughness was improved with this post-processing technique (Singh & Davim, 2019).

However, as could be expected, these techniques are not appropriate for every kind of material. As an example, flexible materials are difficult to post-process mechanically. For this reason, non-planar 3D printing is an interesting pre-processing technique that could be further combined with post-processing in order to achieve very good surface quality.

This paper will thus address the development of a robotic 3D printing unit dedicated to large scale (about 1 $m^2$) pieces and the work dedicated to the optimization of this new printing process. In such a process, the most challenging part is obviously the development of the software controlling the trajectories, as can be seen in the literature. Considering the difficulty of finding commercial software solutions, this paper will focus on the development of the trajectory planning system.

## 2. Material and methods

The robotic 3D printing unit (Fig. 1) is composed of different entities:

- a Staubli TX2touch 90L robotic arm with a reach of 1200 mm and a payload of 10 kg;
- a Massive Dimensions MDPH2 pellet extruder, highly customized in the frame of the project in order to be sufficiently robust, more silent and reliable in terms of pellet feeding;
- a tailor-made heat plate to reduce the warping phenomenon and improve the adhesion of the 3D printed parts;
- control electronics based on various microcontrollers and temperature regulation.

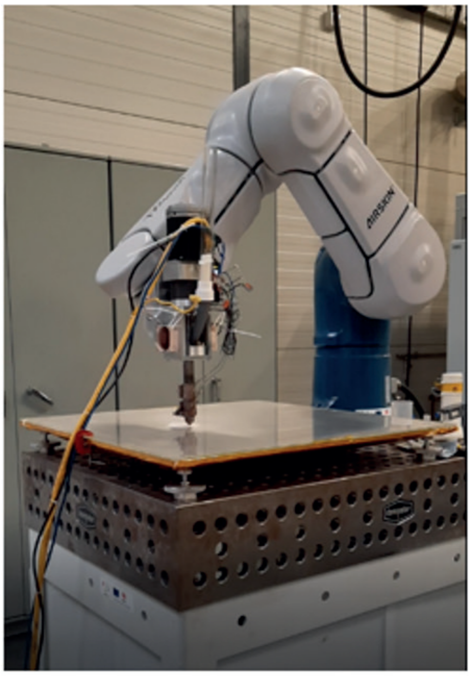

**Fig. 1.** Robotic 3D printing unit

### Generation of trajectories and optimization of the 3D printing process

In order to be able to 3D print with such a unit, the first step was to synchronize the robot's movements with the extruder flow rate. Indeed, the melted polymer flow rate has to evolve in accordance with the robot displacement speed so that optimal extrusion can be obtained all over the structure.

As the robot controller is unable to generate the required signals for the extruder, a custom signal logic is required. Using an Ethercat coupler, digital and analogue signals and a custom microcontroller, it was possible to create a high-speed control loop which can dynamically adjust the extrusion parameters.

A custom G-code to VAL3 post-processor was written to synchronize the movement and differentiate travelling from working movements, as well as to compute the amount of material to extrude and the signals to be sent to the microcontroller. With this development, the 3D printing unit is able to read and translate the G-code file coming out of slicers, as explained below.

Trajectories for 3D printers are written in G-code, a machine tool language. In this syntax, movement coordinates are given as a [X, Y, Z] 3D vector, and the amount of material to extrude for a path in the movement is given as a single "E" value.

In contrast, robots work in 3D space. Their tool position ("tool frames") are a composition of a 3D translation matrix and three 3D rotation matrices within an absolute coordinate system. As such, the post-processor needs to transform the G-code vector to a translation matrix, as well as to extrapolate the rotation matrices. For 3-axis printing, the rotation components can be fixed as the printing head does not need to tilt, which greatly simplifies the work. For 5-axis printing, the Euler angles would be computed by the slicer as input to the post-processor, if a collision check was performed. In the frame of the project, the printing unit is restrained to 3-axis to facilitate the integration of the developments on the ISF equipment, which is a cartesian machine.

In order to synchronize the extrusion with the movement, commands are given to the extruder based on the planned trajectory length, G-code "E" values, as well as the dynamic parameters of the system (acceleration, deceleration, trajectory blending, …). This value is highly dynamic and must be perfectly synchronized with the movement without overloading the robot controller.

Trajectory planning is then done through conventional 3D printing means. A specific file format (3mf, stl, obj) is used to represent the object to be printed as a succession of triangles approximating the final geometry. This mesh is imported into a piece of software called a slicer. This slicer performs different steps:

1. Reads the entire file and caches each triangle by its vertices and normal vector.
2. Finds and classifies the contour of the object as external walls, holes, top and bottom surfaces.
3. Performs a mathematical intersection of the triangles following the Z axis at a regular interval, defined by the layer height.

4. Plans the trajectory from the edges obtained in the last step and fills the contours with a regular pattern of a controlled density.
5. The material to add for each line is then derived from the layer height, line thickness and properties of said line.
6. The file is exported as a G-code file.

The G-code is then converted into a language readable by the robot thanks to the custom VAL3 post-processor.

The first 3D printing trials were then carried out with PLA in order to realize dies for the ISF process (Fig. 2). These first parts were of intermediate quality, with some "bumps/blobs" observed on the surfaces (Fig. 3). These defects are mainly because the robot stops for a very short time at certain locations between two consecutive movements. Moreover, in opposition to a conventional FDM extruder, it is impossible to retract the filament with the pellet extruder. So, when the movement is stopped, the residual pressure left in the extruder causes the melted polymer to flow freely from the nozzle, and defects consequently appear on the surface.

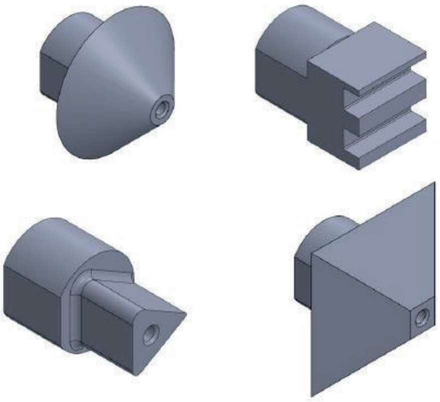

**Fig. 2.** CAD model of the dies

**Fig. 3**. Illustration of the surface irregularities

In order to improve the surface quality, it was thus necessary to improve the predictive execution of the extrusion instructions by the robot using asynchronous processing. With this in mind, the robot was able to achieve smooth transitions between consecutive movements. The modifications also allowed the extruder instructions to be slightly desynchronized with the end of the previous movement. Thanks to this, the system was able to use the residual pressure in the extruder to print the last millimetres of each line. The difference in the printing quality with such a technique is obvious (Figs. 4 and 5). It also opens the way to non-planar 3D printing, which consists of very short trajectories and whose printing quality is very dependent on the absence of interruption between consecutive movements.

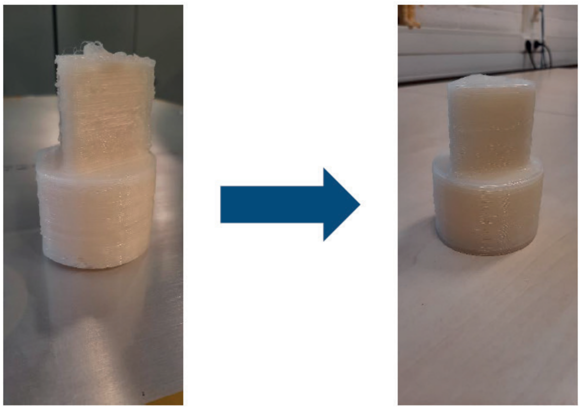

**Fig. 4.** Comparison of pieces with (right) and without (left) predictive execution

**Fig. 5.** Final pieces with residual pressure compensation

## Non-planar 3D printing

At that stage, the 3D printing unit was able to realize pieces layer-by-layer, inducing the stair-stepping effect on surfaces, especially visible on curved top surfaces. A way to improve the surface smoothness is to use non-planar 3D printing in order to follow the curvature of the pieces while printing (Fig. 6).

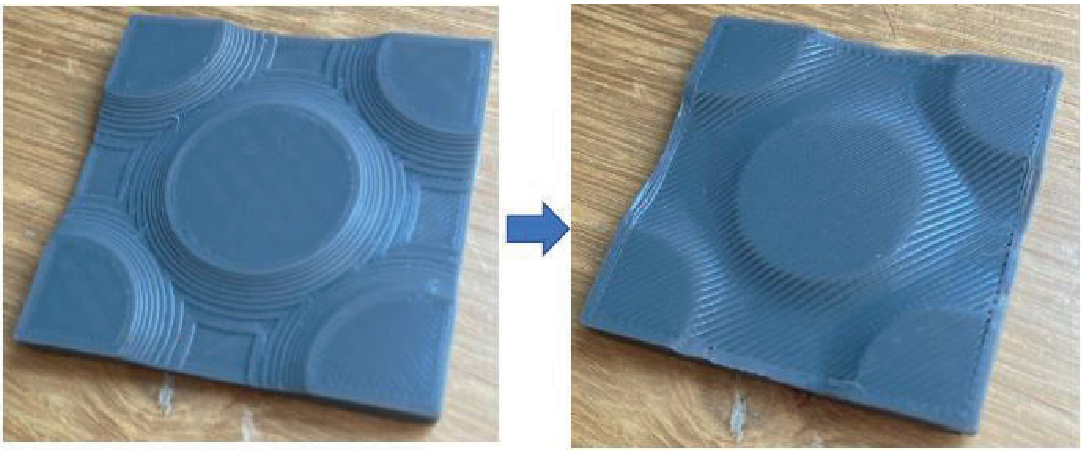

**Fig. 6.** Improvement of surface quality using non-planar 3D printing

To generate non-planar trajectories, a modified Slic3r software was used. It takes into account the geometrical limitations of the extruder to identify the potential non-planar printable surfaces. Then, it generates trajectories using geometrical projections so that real 3D movements are created. Finally, a G-code file is obtained and used by the robotic 3D printing unit. Demonstration pieces were obtained, such as those illustrated in Figs. 7 and 8.

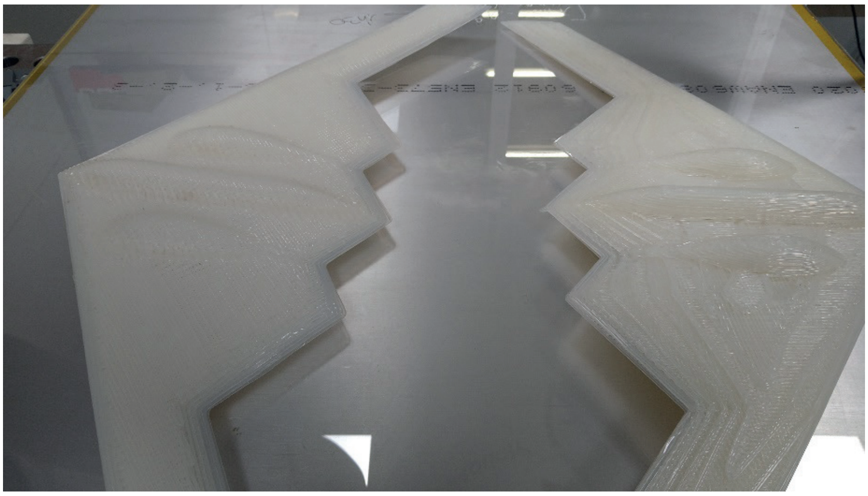

**Fig. 7.** B-2 Spirit bomber, non-planar (left) vs. planar (right)

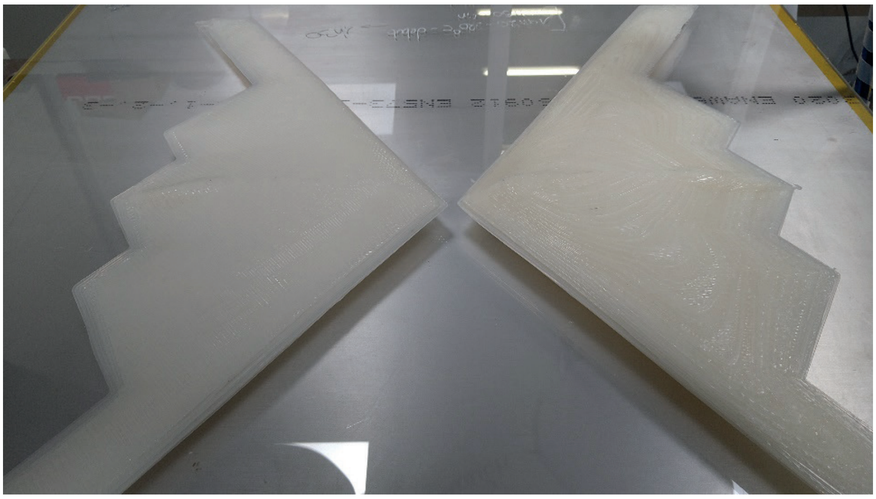

**Fig. 8.** B-2 Spirit bomber, non-planar (left) vs. planar (right)

Despite displaying considerable improvements in surface quality, non-planar 3D printing still presents some challenges. Indeed, in the software, the non-planar printable surfaces are first identified and then projected onto a plane. The printing trajectories are defined in that plane and projected back on the original non-planar surface. The obtained trajectories are not necessarily distributed evenly on the surface, nor spaced correctly, and it causes over-/under-extrusion problems directly visible on the surfaces of the printed pieces. As an example, the curvature is more important on the top face of the B-2 Spirit and it results in a less smooth surface compared to the bottom face (Figs. 7 and 8). This limitation is at the root of the Slic3r software, used to generate the trajectories, and the possibilities to solve it without a rewrite are very few in number. The components of the slicer were extended to use a dynamic Z, but the math, path planning, extrusion calibration are all done in a projected 2D space, resulting in imperfections based on the curvature. The first obvious solution is to limit the admissible curvature of surfaces to be printed in a non-planar way. Other surfaces will thus be printed in a classical manner. The best work-in-progress alternative chosen in the project is the development of a custom non-planar slicer dedicated to the robotic 3D printing unit.

## 3. Results

The aim of this work was to improve the surface quality of 3D printed pieces so that metal sheets can be shaped on them according to the ISF process. Ultimately, the obtained sheets will have to be of great quality to demonstrate the potential of the combined 3D printing – ISF processes in addition to the obvious environmental incentive.

Concerning the materials, the process was mainly tuned with PLA as warping is limited with such a polymer. The specific grade used in the project was PLA 3D870, especially dedicated to 3D printing, without drying. Mechanical properties of the printed test specimens were then compared to the expected values from the datasheet. For this purpose, parts with specific filament stacking (5 samples each) were realised with the 1.5 mm nozzle to compare with the theoretical properties (Fig. 9). The test specimens are simple parallelepipeds of the following dimensions: L: 200 mm × W: 20 mm × H: 10 mm. The printing parameters were:

- layer height = 1.2 mm,
- nozzle temperature = 210°C,
- heatbed temperature = 70°C,
- printing speed = 50 mm/s,
- infill = 100%.

As this grade is dedicated to 3D printing, the datasheet mentions the properties for 3D printed parts, printed at 100% infill and annealed (NatureWorks, n.d.). The results of the 3 points bending tests are listed in Table 1 below. Despite being close to the expectations, the measured properties still remain below them. This can be explained by the fact that no annealing was performed on the test specimens.

**Table 1.** Average test specimens mechanical properties compared to the datasheet of PLA 3D870

| Mechanical properties | XY axis | YX axis |
|---|---|---|
| Flexural strength – experimental [MPa] | 63.84 | 41.22 |
| Flexural strength – datasheet [MPa] | 73 | 49 |

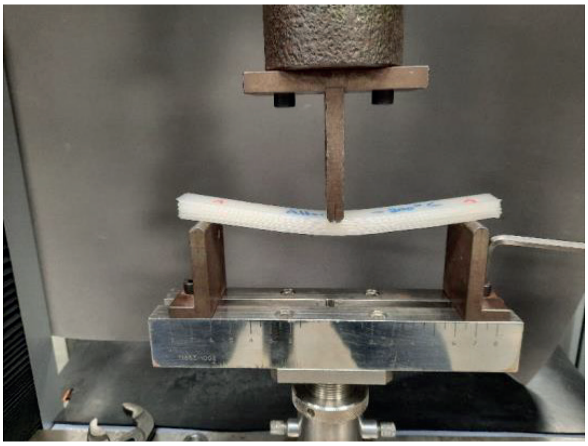

**Fig. 9.** Mechanical testing of the printed specimens

The final pieces for ISF obtained with the process (Fig. 5) were characterized in order to compare the performances of the developed system with commercial FDM printers. It was seen that a good repeatability of ±0.2 mm was achieved with the system. Commercial 3D printers present similar levels of performance, but they print far more slowly and with small diameter nozzles (0.4 mm compared to the 1.5 mm used in this study). Desktop 3D printers would be expected to print similar parts in more than 8 hours while the robotic 3D printing unit is able to realize it in about 1 hour (Fig. 10). The surface quality of the 3D printed pieces is then obviously improved by using the non-planar 3D printing technique and the compensation of the residual pressure (Figs. 7 and 8). Measurements of the surface quality were not realised as the pictures are already very relevant. However, 3D scans could have been realised to evaluate the deviation between the shape of the printed part and the CAD file. In that sense, the dimensional accuracy of non-planar 3D printed parts would have been better. Thus, complex dies could be created for ISF with this technique. Finally, 3D printing quality is always a compromise with printing time. The choice of nozzles with larger diameters is a very interesting option to reduce the printing time of massive pieces necessary for ISF but the details and the surface quality are, in general, far less accurate with such nozzles. However, the developments presented in this paper promote higher printing quality and maintaining a high production rate by using improvements of the control software based on a deep analysis and understanding of the robotic 3D printing process.

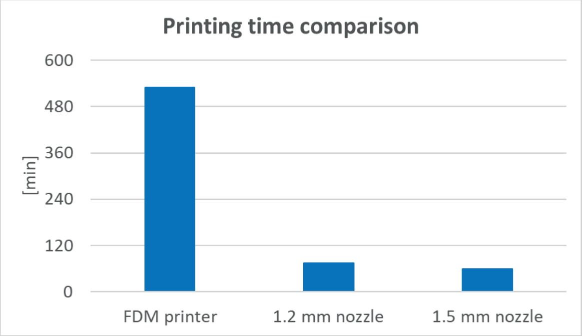

**Fig. 10.** Printing time comparison between classical 0.4 mm nozzle FDM printer – 1.2 mm nozzle robotic 3D printer – 1.5 mm nozzle robotic 3D printer, for the manufacturing of ISF dies (diameter 70 mm – height 100 mm)

## 4. Discussion

As can be seen in the literature, robotic 3D printing is generally limited to single-wall printing. The developments realised in this project enabled the control of the walls and infill printing which is of great interest for future applications and the mechanical properties of the forming dies are not negligible. For this reason, three-point bending tests were carried out on printed test specimens. As the mechanical properties of PLA are very different according to the selected grade, it is difficult to find relevant comparisons. Typical flexural strength encountered for PLA in FDM 3D printing ranges from about 50 Mpa to 115 Mpa (Nugroho et al., 2018). As similar experiments were not found in the literature, the most appropriate point of comparison to discuss the results is the datasheet of the PLA 3D870 material. As summarized in Table 1, the experimental strength is about 15% smaller than the expected results. However, the test specimens were not annealed, and this is probably the reason for this difference. The literature shows that annealing increases the strength by 10% to 20% (Carolo, 2021).

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