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INFLUENCE OF CONSTRUCTIVE PARAMETERS OF FDM 3D PRINTING IN THE PIPE WITH HOLE FABRICATION

Dinu Iacob POIANA, Ioana IONEL, Mircea Dorin VASILESCU,
Maria-Monica BORLEANU

Abstract: *In this study, the authors focus on establishing constructive characteristics that can influence the additive manufacturing process of a pipe with hole or a simple pipe with high-speed polylactic acid material. In the paper, after an initial study on the main current aspects of additive manufacturing, the main components used to carry out the study are presented. One of the important elements, along with the dimensional one, was that of the emissions generated in the additive manufacturing process, including CO₂ emissions. Next, the main constructive elements that affect the manufacturing process are detailed and determined in the logical order of the implications in the manufacturing process.*

Keywords: 3D printing, additive manufacturing, dimension parts, PLA material, FDM printing.

1. INTRODUCTION

An important technological component that has emerged recently is that of additive manufacturing, using thermoplastic materials to make tubular elements that are used not only in automotive engineering but also in other industrial fields.

Obtaining small or medium tubular parts with holes can be done traditionally by processes of perforation and plastic deformation to the desired shape. The process is complex and high energy consuming. This energy can be generated by processes that are not environmentally friendly, such as coal, or relatively environmentally friendly, such as nuclear energy.

Some of these solutions are used in the heating or heat transfer part [1- 3]. It should be noted that most of the pipes used in the thermal field are obtained from powders, as can be seen from the three previous references, using the laser beam or the electric arc as the energy source.

Thus, a group of researchers coordinated by Szymanski [1], analyzes the production of large-scale heat pipes using the manufacturing technology developed by HP. The issue of

small-diameter cooling pipes made using additive manufacturing specific to the field of electronic cooling components was addressed by a team of researchers coordinated by Maroosol Yun [2]. It can be seen from the presentation, but also from the study carried out by the team coordinated by Kuan_Lin [3] that the issue of long pipes for heat exchange is very important in the industrial field, but also in that of electrical engineering. A great advantage of manufacturing long pipes with or without holes, with complex planar or spatial geometry can be achieved much easier and more economically through additive manufacturing, reaching up to ten times cheaper, as shown by a group of researchers coordinated by Fica [4] in the case of manufacturing pipes through the thermoplastic process with ABS for the production of gas reduction hoses in water well drilling installations.

Another direction in which such components can be used that are subject to analysis is in the hydraulic field [4, 5]. In addition to the pipes part, in the hydraulic industry as can be seen from the study carried out by the team coordinated by Abel R. [5], the rotors of turbines, pumps, respectively compressors or fans should also be included.

The pipe part or in other words the tube is made to optimize the flow and reduce the cavitation effect due to the very good quality of the inner surfaces made, using additive manufacturing technologies, especially with resin of the type (DLP, MSLA, SLA) [6].

However, the additive manufacturing solution of FDM or FFF-FDM type with engineering materials such as PEEK should not be neglected, as analyzed by the team coordinated by Domen, S.D. [7], or with semi-industrial or biodegradable materials such as PLA (PLA-NX or PLA-PC), PETG or ABS, as analyzed by the team coordinated by Fică S.A., and others [4].

The study considers both a brief presentation of the materials and methods used in the experimental part, the presentation of the experimental part, and the processing of the dimensional and emission values resulting from their additive manufacturing process. Finally, an interpretation of the research results will be made. The study considers both the determination of temperature and humidity in the printing process, as well as the components of gas emissions total volatile organic compounds (TVOC), formaldehyde (HCHO), respectively CO₂.

2. MATERIALS AND METHODS

2.1 Material

In this study, to observe whether there is an influence of the dye on the printing process, a white and blue filament from POLYMAKER of the Poly Terra type were considered Figure 1.

From the basic data for the printing process, the temperature at the nozzle level must be between 190°C and 230°C; for the printing surface, a temperature between 25°C and 60°C is recommended. For the workspace where the printer is positioned, it is recommended that it be half of the temperature of the surface used for printing. Printing speed must be between 30 mm/sec and 70 mm/sec, with 100% for ventilation of the printing surface.

From the air moisture absorption curve, on the first day, the value is approx. 0.2%. This depends on the conditions in which the filament is arranged in the workspace.



Fig. 1. PLA+ from POLYMAKER of the PolyTerra.

It can also be seen from the deflection diagram as a function of temperature, which is zero up to almost 52°C, for a pressing force of 0.45 MPa. Also, the wire retraction parameters during periods when printing is stopped due to the transition from one layer to another or between printing areas are dependent on the way in which the wire is extruded, and for the case of the printer used. It is recommended that the retraction value to be between 2 mm and 3 mm, with a speed of 40 mm/sec.

2.2 Printer

A TRONXY XY-2 PRO cartesian printer was used, equipped with a single nozzle to extrude the material Figure 2 for the experiment.



Fig. 2. TRONXY XY-2 PRO cartesian printer.

From a constructive point of view of the printer, the table movement is in the Y direction for printing pipe, and the nozzle makes translation in the X and Z axes. The printing volume dimensions are 255x255x260 mm. The printer is an I3 PRUSA type, with automatic level detection and 16 points on the printing surface for automatic calibration.

The printing speed is between the limits of 20 mm/sec and 100 mm/sec, which is in the recommended speed range for the material chosen for this study. The layer thickness that can be achieved is between the limits of 0.1 and 0.3 mm for a nozzle with a diameter of 0.4 mm.

He is made of brass, with its standard E3D geometry. The importance of the nozzle type is given by the flow process of the extruded material. The maximum nozzle temperature is 275°C and the high temperature for surface printing is 120°C. It is possible to observe that both are within the recommended temperature range for the chosen material. The recommended ambient temperature is between 8°C and a maximum of 40°C. An important characteristic, as observed for the material used for printing, is the humidity of the space in which the printing is performed, which, from the machine's point of view, is between 20% and 80%.

The nozzle diameter is a very important constructive parameter that could influence the printing quality, emissions and cost of the generated parts. If the nozzle diameter is larger, then more material is deposited on the printing surface, but at the same time, it will have a larger generated line width and a lower quality/precision of the part surface. Most printers are constructed with a 0.4 mm orifice diameter, but for finer precision parts can be made by printing with a 0.3 mm nozzle. A relatively acceptable precision can be obtained with 0.5 mm nozzle. Larger nozzles, such as 0.6 mm are at the limit.

Along with the previously mentioned factor, one must also consider the one that influences the geometry of the deposited layer, which is the distance from the extrusion orifice and the surface on which it is performed. The latter can produce for lower values a higher extrusion force with higher energy consumption and, respectively, a larger size of the deposited material section. The choice of this parameter depends on the printing speed, the wire pushing speed and the nozzle diameter. A higher printing speed will reduce the generated thickness and, implicitly, the achieved thickness and vice versa. Some authors recommend a ratio of 1/4 to 3/4 of the diameter in rapport with the distance. Given these previously mentioned observations, we printed the pipe presented in Figure 3 with a 0,2 mm height.

The settings chosen were 0.2 mm for the layer thickness (1/2 like rapport), with 0.30 mm for the first layer, alternating number of layers 1,5

(alternative line inner for each 2 layer), layer density 30%, no/with supports, 65°C printing surface temperature with 210°C for the nozzle. The chosen printing speed was 50 mm/sec, the rest of the speeds were selected at 30 mm/sec.

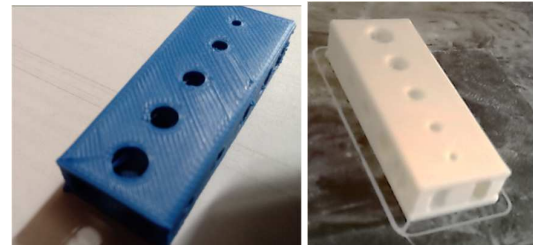


Fig. 3. Pipe 20x10 mm with hole diameters 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, left blue and right white.

2.3 Slicer

The program used to generate layers was IDEAMAKER 5.2.0 for some facilities. The program recommended by the manufacturer, REPETIER HOST, does not have this option of configuration this option. It should be noted that neither the program that accompanies the previously presented TRONXY SLICER printer allows for the creation of some printing settings that the first program has. The first two most important settings are related to the continuity of the printing line at the periphery of the outer lines of the generated contour Figure 4. The second is the alternation of the lines located on the outer or inner side of the generated contour Figure 5.

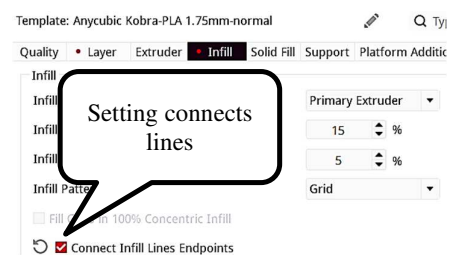


Fig. 4. Continuity of the printing line at the periphery of the outer lines.

An important aspect considered in the layer generation part was the continuity of the infill lines. Also of great importance is the increase in the bond strength between the perimeter layers and the infill area which is presented in Figure 6.

Although these are not constructive factors, they are important in the printing process.

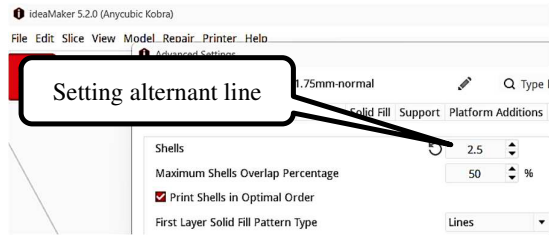


Fig. 5. Alternation of the lines located on the outer or inner side of the generated contour.

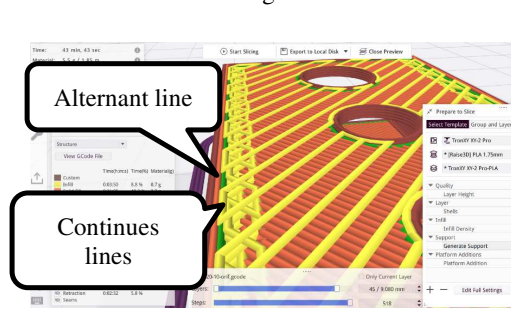


Fig. 6. Pipe 20x10 mm with hole printing solution.

2.4 Measuring devices

The measuring device for pipe dimension is digital caliper, with a measurement accuracy of 0.01 mm. For measuring gas emissions during the printing process that were presented in the works [8, 9] are used and we will not insist on them anymore, because in those works all the specific aspects of both calibration and comparison of measured values with semi-industrial individual emission measurement sensors were presented Figure 7.

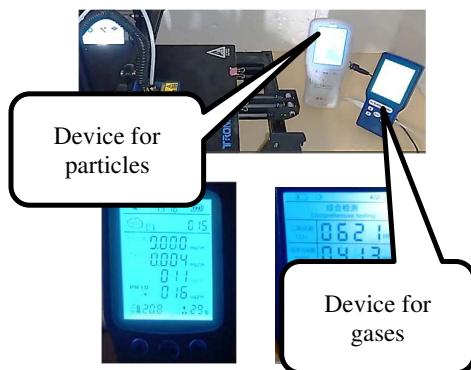


Fig. 7. Measuring gas emissions in space for printing processes, top position, bottom position left TVOC-HCHO-Temp-Humid, right CO₂.

The measuring device on the left shows a humidity in the workspace of 29%, which is very

good compared to the exposure conditions of the printing wire but also a temperature of 20.8°C.

The initial parameters of the space in which the printer is located were determined by measuring together with the entire assembly, printer turned on, filament inserted into the nozzle and before loading the program for printing. On the second device on the right, the CO₂ level is 537 ppm, the TVOC 0,21 ppm, and the HCHO is 0,029 ppm.

2.5 Method

The geometry and dimensions of the pipe-type elements with holes were relatively short in order not to lengthen the printing process Figure 8. The holes were offset on the periphery of the pipe at 90° from each other to determine whether there is an influence of the hole position in relation to the angle of inclination relative to the printing process.

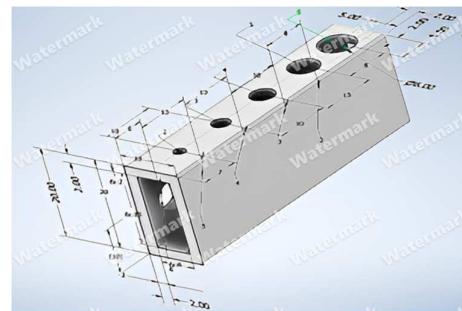


Fig. 8. Pipe 20x10 mm with hole standard setting vertical CAD wall.

An important aspect of carrying out CO₂ emission measurements is the presence of the operator in the workspace. His influence is all the greater the closer he is to the emission measurement area. Considering this aspect, we developed a study in which the operator was not in the room where the emission measurements were taken Figure 8, left. The value of CO₂ is 539 ppm, TVOC 0,102 ppm, and HCHO 0,014 ppm, AQI for TVOC is 2, and environmental quality is good. After that, the measurement was carried out with the operator in the room. The 2 meters by 4 meters and with a height of 2.5 meters are the dimension of the working space, and subsequently with the operator in the emission measurement device Figure 9 right present the value of CO₂ is 779 ppm, TVOC

0,919 ppm, and HCHO 0,126 ppm, AQI for TVOC is 2, and environmental quality is good/pollution.



Fig. 9. Emission in the room without the operator left and with operator right.

3. RESULTS AND DISCUSSIONS

To obtain elements such as pipes, efficient generation methods are different, and the costs of the resulting parts vary in the direction of increasing or decreasing them. This study aims to determine whether pipes made from materials such as aluminum or copper can be replaced with those that can be recycled after their end of use. The normal PLA material was initially chosen, and subsequently, based on this study, materials reinforced with fibers or combined with polycarbonate that have characteristics superior to the base material will be used in other study.

3.1 Constructive parameters of printing

As can be seen, there is a correlation between the diameter of the nozzle orifice and the distance between its front part, as recommended by experimental studies previously conducted for prismatic structure [10]. Due to this fact, a set of experimental tests was carried out in which the previously mentioned distance was modified by a difference of 0.05 mm from the median value recommended by the manufacturer for the 0.4 mm nozzle.

The vertical distance influences the realization of the horizontal structures, therefore implicitly the thickness of the pipe in the horizontal generation plane. It should be noted that the structure is formed in the horizontal plane by two layers with 100% density between which one or more layers with a modified structure are found. Also, for the pipe structure, he has a previously mentioned structure, both in its lower and upper parts. The difference

between these two types of structures is given by the fact that at the bottom we have a first layer of adhesion with a greater thickness, and the rest of the layers will have equal thickness.

In Figure 10, we can see a version of the pipe designed to be made with the standard settings proposed by the program, namely a solid layer at the base of 0.3 mm, five solid layers at the base of which four are 0.2 mm, so the thickness of the lower part of the pipe is 1.10 mm Figure 11.

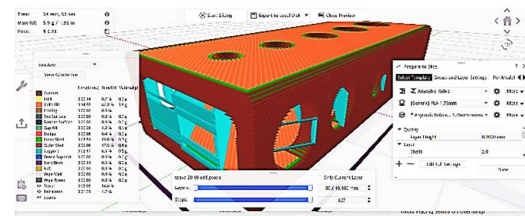


Fig. 10. Pipe 20x10 mm with hole standard setting for printing.

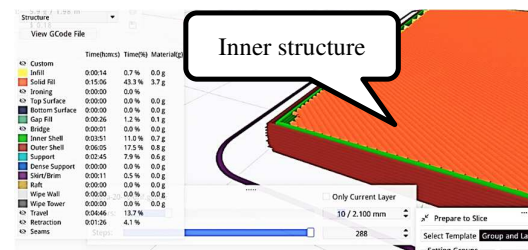


Fig. 11. Pipe 20x10 mm with hole standard setting bottom wall.

The vertical side parts start from the sixth layer and end at layer 40, so we have 8.10 mm from which we subtract 1.10 mm, resulting in a vertical wall of 7.00 mm. The upper part of the pipe starts from layer 41 and ends at layer 50, which makes the total height of the vertical part of the pipe 10.10 mm, with a thickness of the upper plate of 2 mm.

An important aspect is related to the creation of horizontal walls, noting that at the bottom it starts from layer 1 and reaches its surface which ends at layer 10 with a value of 2.10 mm on the program generation side (0.30 mm + 9*0.2 mm) and for the vertical one which starts from layer 41 with a value of 8.30 mm and ends at the final layer number 50 with a value of 10.10 mm (10*0.2 mm).

An important issue is the side walls and the position of the large diameter hole relative to the edge of the vertical wall of the pipe. In Figure 12 we have a wall thickness of 2 mm with two

perimeter lines and a diagonal thread at 45 degrees.

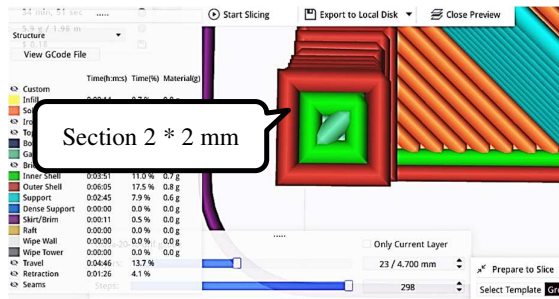


Fig. 12. Pipe 20x10 mm with hole standard setting vertical GCODE wall.

Considering that the nozzle diameter is 0.4 mm we have a thickness achieved on the generating side of 2 mm which is the wall thickness ($2 \times 0.4 \text{ mm} + 0.4 + 2 \times 0.4 \text{ mm}$).

A rather important dimensional aspect is the determination of the section in the diametrical plane in the case of the perimeter holes. As can be seen from Figure 13 for small sections of 2 mm by 2 mm, the infill part at a density of 15% does not exist and from the determinations made according to the nozzle diameter this will not be possible either. If we reduce the nozzle hole diameter to 0.3 mm in this case the generation of the internal structure is not possible either. It therefore follows as a conclusion from a geometric point of view, to obtain a structure with relatively good characteristics the minimum section must be larger.

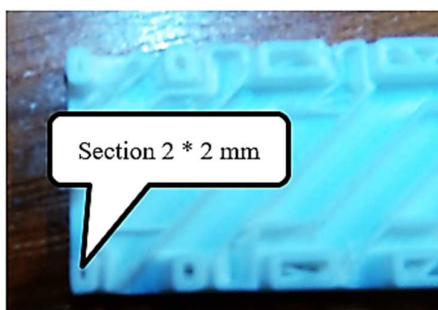


Fig. 13. Pipe 20x10 mm with hole standard setting for 2 mm or 2 mm section printed.

However, if we activate the setting options mentioned in the layer generation program selection section and reduce the nozzle diameter to 0.3 mm while maintaining a layer height of 0.2 mm, we can see that the program is also

capable of creating interior lines, the yellow ones, Figure 14.

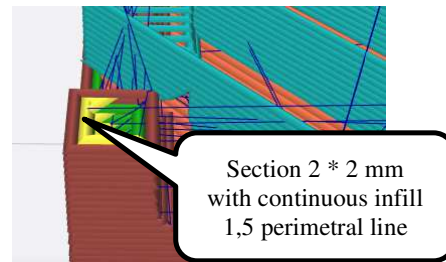


Fig. 14. Pipe 20x10 mm with hole standard setting vertical wall 2 mm or 2 mm.

From what is presented, an important conclusion is reached that both the nozzle diameter and the choice of line generation in the printed layer are important in determining the minimum section that can be achieved with good constructive characteristics. For the 0.4 mm nozzle in the simulations performed, a 6 mm by 6 mm section would be optimal without the two-line generation settings mentioned.

In Figure 15 top left position, it can be seen the method of material deposition for the size of 5 mm by 5 mm. In the right top position with the 1.5-line setting it is possible to observe the line generation. At the bottom of Figure 14 it is presented the solution with the continuity of the inner printing line. We mention that the study was undertaken for the same material deposition generation layer.

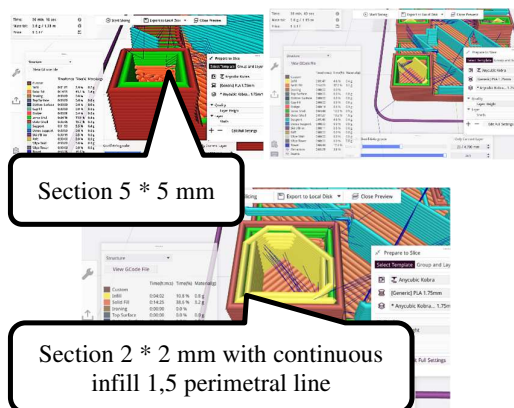


Fig. 15. Pipe 20x10 mm with hole standard setting vertical GCODE wall 5 mm or 5 mm top left standard, right with 1,5-line, bottom continuous line.

The graphical analysis considers the dimensions of the lines and layers in the

visualization offered by the layer generation program. For the study we will use the educational version of the INVENTOR program, taking the images of the holes from the vertical direction and placing the pictures on the drawing surface of the previously mentioned program interface Figure 16.

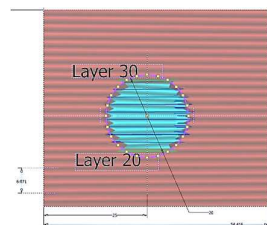


Fig. 16. Holl 2 mm in vertical position of pipe 20x10 mm 0,20 mm layer height.

The picture of the chosen section was imported into the INVENTOR program and processed, first by resizing to obtain a layer thickness of 0.20 mm (a scale of 10/1 was used), so on the graph we have a thickness of 2.00 mm for the layer. The hole is between the continuum layers 20 and 30 respectively. We entered the circle with a diameter of 20.00 mm, and it fits between the triangular areas on the graphic interface but also penetrates the lower and upper continuous layer area. It can also be observed that the circularity of the hole, no matter how precisely it is graphically realized, will not have such a shape due to the way the layers are generated. With these we can make the correlation between the number of layers and diameter, resulting in 24 peripheral points, as can be seen in Figure 17.

Considering the programs mentioned as recommended in the subchapter regarding the layer generation program, they were analyzed for generating lines for a 2 mm vertical hole, as can be seen in Figure 16, resulting in the same problem observed in the previous study.

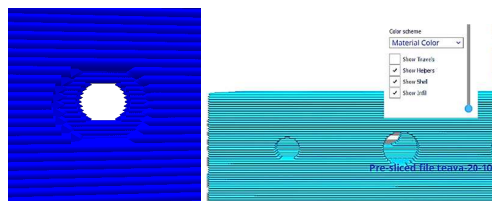


Fig. 17. Holl 2 mm in vertical position layer height 0,15 mm left REPETIER HOST, right TRONXY.

To verify the concordance between the previously performed analysis method, for holes generated in the vertical wall, the authors extended the study in the direction of verifying the way in which the command lines are created in the G-CODE command program. To analyze the way the layers are generated, as can be seen from Figure 18, the sequence of lines was inspected based on the points generated by the nozzle in the figure.

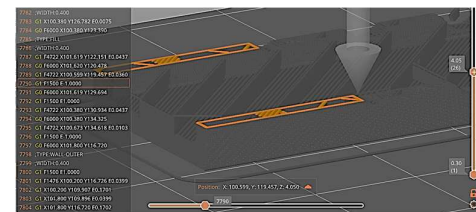


Fig. 18. Holl 2 mm in vertical position G-CODE VIEWER.

The dimensions of the free space along the Y direction were determined. It can thus be observed in Figure 18 that there is an important influence of this ratio in the non-uniform way of generating the circular section. The non circularity for the layer height of 0.20 mm is relatively symmetrical in the horizontal plane, but in the other two variants this is no longer repeated. The asymmetry is greater the thicker the generated layer.

The previous aspect resulting is even more important since in the vertical direction, as will be seen from a dimensional point of view, there is a compressive stress that additionally influences the circular shape of the hole.

In Figure 19, the circular appearance of a 2 mm hole generated on the printing surface of the last layer can be observed.

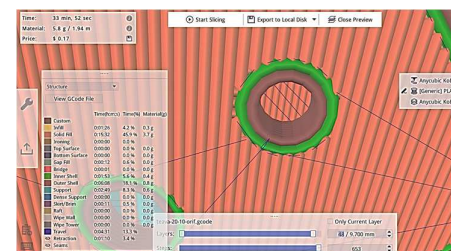


Fig. 19. Holl 2 mm in horizontal position pipe 20x10 mm.

From a dimensional point of view, one aspect considered is that of external dimensional

deviations which have been centralized in Table 1.

From the analysis of the deviations determined between the nominal and the actual elevation, it can be observed that they are positive in the horizontal directions and negative in the vertical direction. This leads us to state that in the vertical direction there is a contraction due to the pushing forces of the material in the generating surface, and in the horizontal plane there is a dilation. This phenomenon has an additional influence on the non-circularity of the vertical holes.

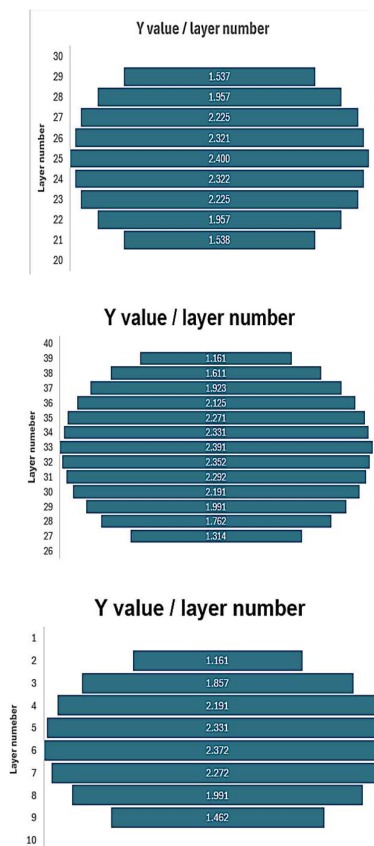


Fig. 20. Holl 2 mm in vertical position layer height 0,2 mm top, layer height 0,15 mm middle position, and layer height 0,25 mm bottom position.

3.2 Emission gases and particle data in printing process

In parallel with the study of the dimensional behavior of the thermoplastic manufacturing of pipes, the study of the evolution of emissions during the additive manufacturing process was also carried out. The levels of temperature change in the workspace were monitored as the printing was carried out Figure 21.

From the temperature evolution during the printing process, an increase can be observed. The evolution is mainly due to the heat dissipated by the printing surface.

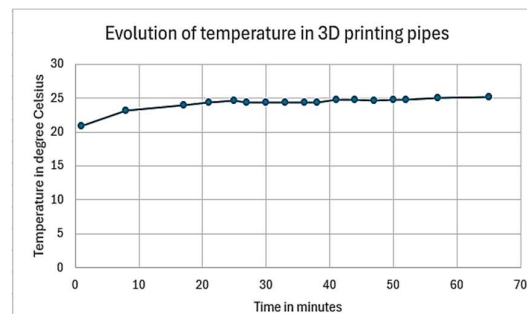


Fig. 21. Temperature evolved in time for 3D printing pipe.

From the study of the evolution of humidity Figure 22, in the manufacturing process of pipe, a decreasing change can be observed, especially with increasing temperature. At the end of printing an increase can be observed because the printing surface is decoupling from the power supply, but also because of the other consuming elements such as motors, nozzles, etc.

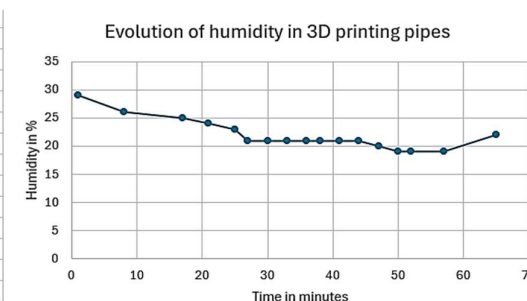


Fig. 22. Humidity evolved in time for 3D printing pipe.

Table 1

Dimension	CAD [mm]	Printed [mm]	Deviation [%]
Ext. Length	50,00	50,09	0,18
Ext. Width	20,00	20,03	0,15
Ext. Height	10,00	9,52	-4,80
Ins. Width	16,00	15,61	-2,44
Ins. Height	6,00	5,82	-3,00

In the case of TVOC gas emissions Figure 23, but also HCHO Figure 24, a similarity in their evolution is observed with a greater increase in the first part of the printing and subsequently the increase is very small.

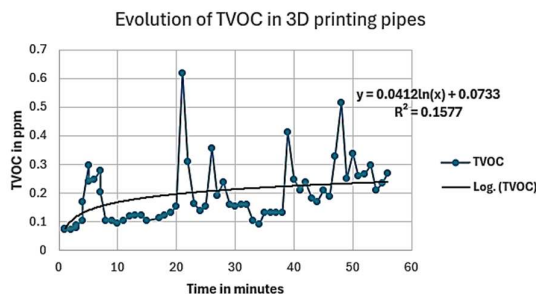


Fig. 23. TVOC emission for 3D printing pipe.

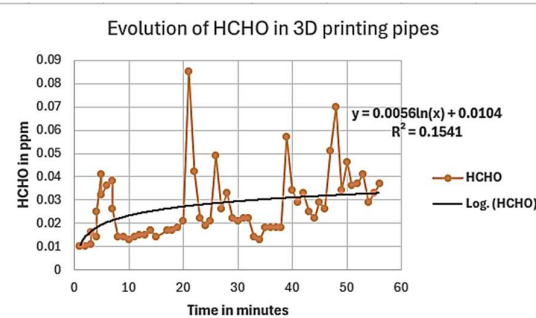


Fig. 24. HCHO emission for 3D printing pipe.

A relatively similar evolution can be observed for the case of CO₂ emissions Figure 25. It should be noted that for all three cases the mathematical regression equation that gave the best value is the logarithmic one.

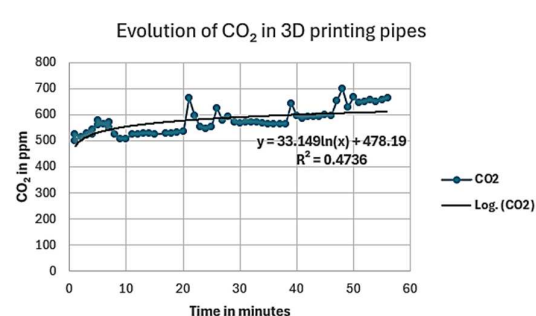


Fig. 25. CO₂ emission for 3D printing pipe.

4. CONCLUSIONS

This study was intended to be the beginning of the investigation of the additive manufacturing of pipes with holes, or of simple pipes that would replace the conventional variants of making such parts and bring an increase in environmental protection. The study was able to demonstrate that in the additive manufacturing process, but not only, the way in

which it is carried out, it has a greater or lesser influence on the environment. At the same time, it was demonstrated that there are correlations between the dimensional constructive characteristics, both in terms of the pipe wall thickness, but also of the geometry of the hole depending on the chosen parameters of additive generation of the layers. The most important were the constructive ones that have an influence on both the geometric dimensions, but also the shape of the holes. From what is presented, an important conclusion is reached that both the nozzle diameter and the choice of line generation in the printed layer are important in determining the minimum section that can be achieved with good constructive characteristics.

The previous aspect resulting is even more important since in the vertical direction, as it was presented from a dimensional point of view, there is a compressive stress that additionally influences the circular shape of the hole. This leads us to state that in the vertical direction there is a contraction due to the pushing forces of the material in the generating surface, and in the horizontal plane there is a dilation.

Finally, it was demonstrated that from the point of view of the level of emissions, they are relatively low, with a slight increase at the beginning of the printing process and very low and not significantly influenced by the modification of the section that is generated through additive printing.

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Influența parametrilor constructivi ai imprimării FDM asupra țevelor cu orificii

În acest studiu, autorii se concentrează pe stabilirea caracteristicilor constructive care pot influența procesul de fabricație aditivă a unei țevi cu orificiu sau a unei țevi simple cu material de acid poli lactic de mare viteză. În lucrare, după un studiu inițial asupra principalelor aspecte actuale ale fabricației aditive, sunt prezentate principalele componente utilizate pentru realizarea studiului. Unul dintre elementele importante, alături de cel dimensional, a fost cel al emisiilor generate în procesul de fabricație aditivă, inclusiv emisiile de CO₂. În continuare, principalele elemente constructive care afectează procesul de fabricație sunt detaliate și determinate în ordinea logică a implicațiilor în procesul de fabricație.

Dinu Iacob POIANA, PhD. student, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, dinu.poiana@student.upt.ro.

Ioana IONEL, PhD, Professor, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, ioana.ionel@upt.ro.

Mircea Dorin VASILESCU, PhD, Professor, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, mircea.vasilescu@upt.ro.

Maria-Monica BORLEANU, PhD. student, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, maria.borleanu@student.upt.ro.