Studies on the Influence of Process Technological Parameters on Geometric Accuracy in 3D Printing of PLA Parts by FFF Printing Technology

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Abstract. The paper aims to present studies on the influence of technological process parameters on geometric accuracy and surface quality, when printing with 3D printers using FFF (FUSED FILAMENT FABRICATION) technology, using PLA wires, 1.75 mm. The research was carried out using a Creality Ender 3D printer, and the material used allowed the creation of a set of parts with medium geometric dimensions, with flat and circular surfaces. In order to determine the influences on printing accuracy, a number of technological process parameters of the printer have been varied, such as layer height, fill density, print speed, print temperature. PLA thread extrusion (printing temperature) and platform temperature (bed temperature). The 3D printed pieces were designed with SketchUp Pro 2020 in .stl format, also loaded with the printer control program, Ultimaker Cura 4.9.1, and finally and were translated into the .gcode print format. The parts were measured in terms of geometric accuracy, the accuracy of the reciprocal positions of the printed surfaces, as well as the quality of the surfaces in terms of the resulting roughness. There are a number of differences, in some cases significant, so that a number of conclusions can be drawn that can provide information on increasing the accuracy and quality of 3D printed parts in these cases.

Keywords: 3D printing · 3D printer · Parts · Measurement · Accuracy · Process parameters

1 General Considerations

Among the modern technological processes for making parts, with very different characteristics in terms of ability to withstand various external influences (temperatures, environments with different radiations, operation in environments that may be unfavourable to the structure, mechanical stresses and tribological view, etc.), 3D printing processes are being used more and more. These, developed in a very wide range and with the possibility of obtaining pieces of very different shapes and sizes, with the most diverse materials, involve processes of formation of the respective body through a process of

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adding basic material in superimposed layers, under certain specific technological conditions. Thus, the simplest, but also the most popular 3D printing process used especially in the educational environment, is the one called FDM or FFF.

The process of making bodies, parts or certain components from more complex structures, involves the deposition, layer by layer, of precisely dosed quantities of plastic material, heated to appropriate temperatures depending on the composition, until reaching the desired size and shape. This technological process involves the adoption and control of technological process parameters such as melting temperature of the material, deposition speed, layer thickness, temperature of the workpiece support plate, the configuration of the weaving directions of the deposited material structure, etc.

As in any technological process of making parts with simpler or more complex shapes and sizes, there are absolutely a number of unwanted problems that make it necessary to study the causes and their magnitude. Based on these studies, a series of measures can be established to adopt an appropriate specific technological process and especially the possibility of optimal control of technological process parameters. Also, a major importance for a quality print is the correct choice of the material used, depending on the conditions of subsequent operation of the parts. Also, special attention is required in the computer-aided design (CAD) phase, when choosing the conjugate dimensions of parts embedded in a more complex system. We refer here to the dimensional tolerances chosen for these conjugate parts.

A particular problem concerns the dimensional accuracy and the corresponding quality of 3D printed parts or components which, due to undesirable disturbing phenomena, show smaller or larger deviations from the dimensions or from the reciprocal positions of the surfaces. These phenomena can occur in terms of inadequate thermal parameters, the choice of printing speeds or thicknesses of the deposited layers that lead to major defects in shape or quality of surfaces.

Also, a very important step in establishing a proper technological process is the corresponding setting of the printing parameters present in the specialized programs. For the usual educational applications, several types of such programs are used, such as Alic3r, Simplify 3D or Cura. Of course, the possibilities of these programs are limited, and more complex and high-performance programs are used for industrial applications.

In this paper, the authors aim to present a series of researches on the influence of the variation of some technological process parameters on the dimensional accuracy, the accuracy of the reciprocal positions of the surfaces, as well as the quality obtained by 3D printing. For this, two types of 3D printers were used, namely the Creality Ender 3D type and the Creality CR-6SE type. The two printers work through FDM (FFF) technology. The parts were designed in shape and size with the SketchUp Pro 2021 computer-aided design program in .stl format. The two prints were printed, being ordered through the specialized program Ultimaker Cura 4.11.0. After designing the shape and establishing the necessary tolerances, the .stl file was transferred to the Cura software, and after the "slices" stage, the effective curing stage took place.

For a greater accuracy of the conclusions regarding the disturbing influences, several pieces were designed and printed, with different shapes and sizes, under the conditions of modification of several specific technological process parameters, followed by quota

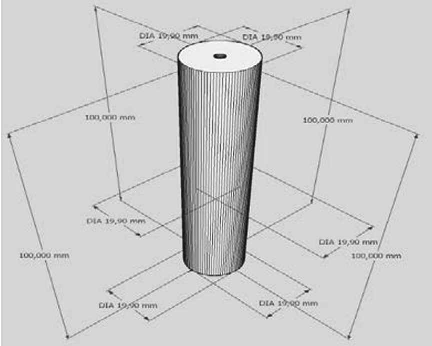

Fig. 1. Cylindrical part with conical centering holes

measurements, reciprocal positions and study of the quality of the obtained surfaces. The material used for the experiments is of the PLA type [5].

2 Design Elements of the Pieces Printed on 3D Creality Printers

For a more comprehensive analysis of the disturbing phenomena that appeared during the process of 3D printing of parts or components with different configurations, we started from the studies developed so far [1–4], as well as the technical possibilities available. Thus, in the first phase, geometric models were made using the computer aided design (CAD) software program SketchUp Pro 2021, considering the program proposed for experimental research. It was chosen for parts with a simpler or more complex configuration, individual or forming an assembly, as well as for a part with a more complex geometry, which would be the basis for precision measurements and quality of surfaces obtained by printing.

A first series of pieces, with simple geometry, can be seen in the following. To determine the deviations from the circularity and cylindricality of the cylindrical parts, a piece with simple geometry was used (see Fig. 1), provided at the ends with two conical centering holes.

The outer diameter, with a size of 19.90 mm, has been established to represent a tolerated dimension that can be conjugated with another cylindrical part with a cylindrical bore with a corresponding dimension.

The conjugate piece, of tubular cylindrical shape with a bore having an inner dimension of 20.20 mm can be observed further (see Fig. 2).

In order to determine the deviations of the parts with intersecting flat surfaces, a set of three components with a square section was designed, of which one in the form of a tubular body with a square section, with an inner side of 20.00 mm, as well as two tubular parts with an outer section also square in shape and with cylindrical and square inner sections (see Fig. 3).

The external dimensions of the conjugate parts, with a side of 10.7 mm, were chosen to represent tolerated dimensions, taking into account the dimensions of the part with which it is assembled.

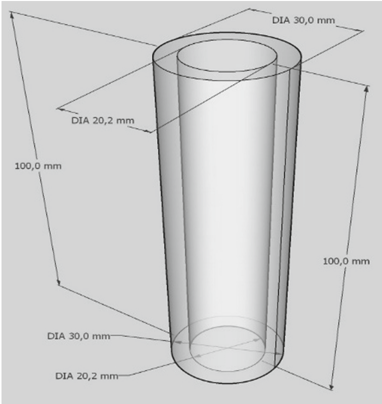

Fig. 2. Tubular cylindrical part

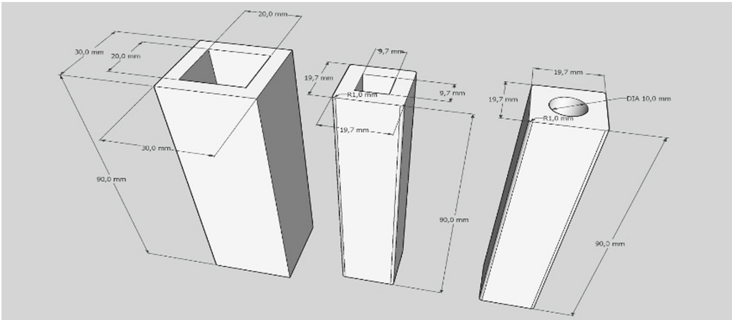

Fig. 3. Conjugated parts with square section

In order to establish both the deviations from the dimensions obtained by printing, but also to determine possible deviations from the reciprocal positions, the variant of a piece with intersecting flat surfaces was chosen, which is provided with two sides at an angle of 90° (see Fig. 4).

In the case of parts with more complex geometry, such as linear coupling conjugate parts with a 'swallowtail' section, the printing accuracy must be superior. In order for them to work properly, the space between the surfaces and the tolerances must be appropriate, and the technological parameters of printing must be carefully chosen. For the study of this case, two conjugate parts were designed, a load-bearing plate with a "swallowtail" profile (see Fig. 5), as well as a wedge-type piece with a "swallowtail" conjugate section (see Fig. 6).

In order to determine as accurately as possible the deviations and disturbing influences that appeared during 3D printing, certain parts were made in two variants, by establishing different base surfaces. In this case, in addition to the variability due to technological process parameters, an important influence is due to gravitational forces.

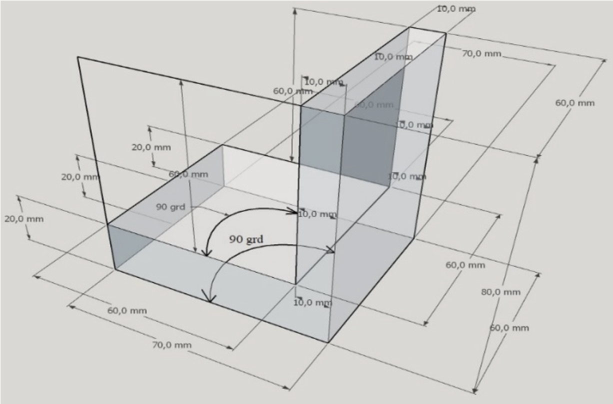

Fig. 4. Plate with sides at 90°

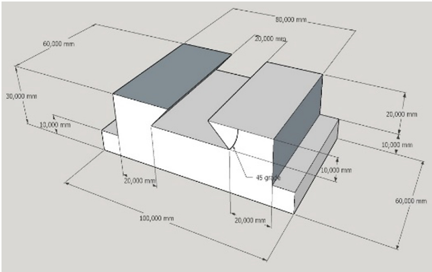

Fig. 5. Swallowtail load-bearing part

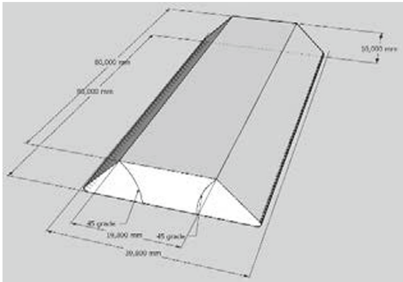

Fig. 6. Swallowtail conjugated wedge

Considering the principle of making the parts, raising the temperature of the PLA material above the melting point and positioning the deposited layers on successive layers, gravitational deformations and inherently deviations from the desired shapes appear. Therefore, some pieces with intersecting flat surfaces were printed on base surfaces arranged at 90 degrees.

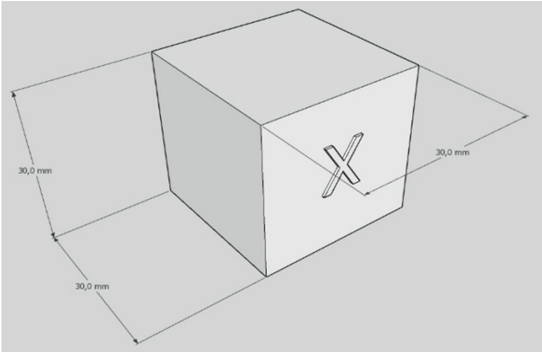

Fig. 7. Cube with side of 30.00 mm

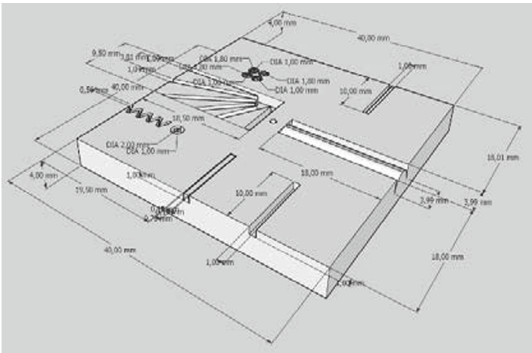

Fig. 8. Part with complex configuration and small details on the surface

A set of parts with a simple configuration, in the form of cubes with a side length of 30.00 mm, was printed in several variants of configuration of the parameters of the technological regime. Thus, the melting temperature of the material, the temperature of the support plate of the 3D printer, the thickness of the deposited layer and implicitly the quality of the printed surface, as well as the printing speed were modified (see Fig. 7).

The last variant of a part with complex geometry was designed and printed in order to determine the influence of disturbing factors and the variation of technological process parameters on the quality of surfaces and the accuracy of small details on its surface (see Fig. 8).

3 Experimental Data on Dimensional Accuracy and Quality of Surfaces Obtained by 3D Printing

The set of parts presented above was subjected to the printing process on the two Creality prints, modifying the technological process parameters, so that a series of comprehensive conclusions regarding the precision and quality of the surfaces can be established.

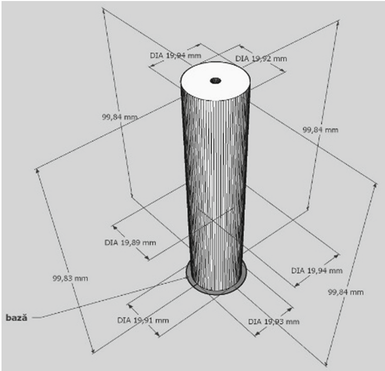

Fig. 9. Dimensions of the cylindrical part

Thus, for measuring the linear dimensional accuracy, a Powerfix electronic caliper model HG00962A with a resolution of 0.01 mm was used, and for determining the deviation from the reciprocal positions of the printed surfaces, a Parkside electronic square model HG00962B was used, with a resolution of 0.1°. The quality of the surfaces and the precision of the small details were measured and visualized with an optical microscope type Bresser_Biolux_NV_20-1280X with the software for visualizing the shapes and dimensions of the parts BRESSER_CamLabLite_x64_2.0.14888.

The previously established elevations were measured, as well as the resulting angles between the flat surfaces intersected at 90°. In the case of the cubic part, the base surfaces were identical, following the dimensions and angles only in terms of changing the technological process parameters.

In the case of the cylindrical part with centring holes, the dimensional deviations are shown below (see Fig. 9), in the situation where the orientation of the part was with the central axis oriented vertically.

It is observed that the diameters have variations between 19.89 and 19.94 mm, so a difference of 0.05 mm, within the imposed tolerance limits. Deviations from the circular shape and the cylindrical shape were determined, considering the dimensions measured at the ends of the part and in the middle. The deviation from the circular shape has a constant value of 0.06 mm, both on the length of 50 mm and on the length of 100 mm, measured on the generators. The deviation from the cylindrical shape varies between 0.01 mm, on the length of 50 mm, and 0.04 mm, respectively, on the length of 100 mm. The deviation from the cylindricality has a value of 0.01 mm, on a length of 100 mm.

The conjugate piece, of tubular cylindrical shape, has values of the outer diameters between 29.94 mm and 29.97 mm, and the inner diameters vary between 20.05 mm and 20.07 mm. In this case, the differences are very small, with values between 0.03 mm and 0.02 mm respectively (see Fig. 10).

Regarding the deviations of the pieces with square section, after the measurement it is found that they vary in limits that allow their conjugation, so that the games are kept within the limits established at the design (see Fig. 11). In the case of the outer conjugate, the deviations vary between 29.97 mm and 30.06 mm on the outside and between 19.82 mm and 20.05 mm on the inside.

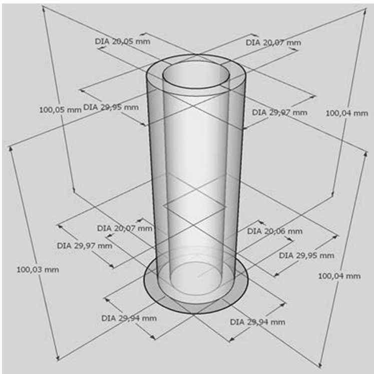

Fig. 10. Dimensions of the conjugated tubular piece

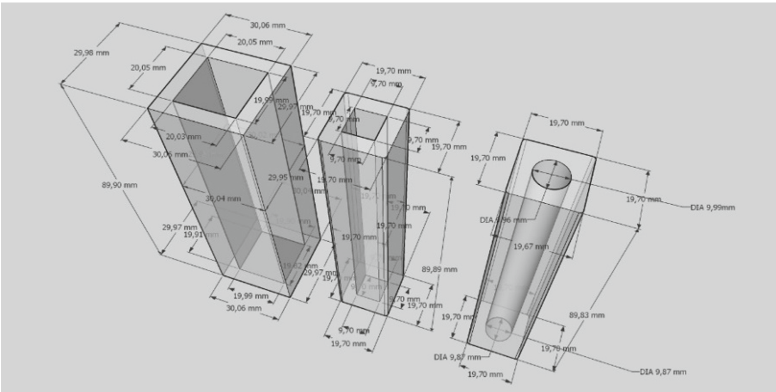

Fig. 11. The final dimensions of the conjugate pieces with square section

After measuring the part with intersecting flat surfaces and two sides arranged at an angle of 90°, it is observed that the dimensions vary depending on the surface chosen as the printing base. The part with the horizontal printing base has the following dimensions (see Fig. 12).

The part with intersecting flat surfaces and the vertical printing base can be seen in the following (see Fig. 13). Analysing the two variants, it is found that the dimensions are kept within tighter limits when using the vertical printing base.

The conjugated parts with "swallowtail" section have the dimensions presented below (see Fig. 14 for the load-bearing part, Fig. 15 for the wedge-type part with vertical base and Fig. 16 for the wedge-type part with horizontal base).

In the case of wedge-type parts, there are differences in printing with different bases, and the version with a vertical base has dimensions with smaller variations. By conjugation, in both cases it can be considered that the tolerance limits prescribed for CAD design are maintained.

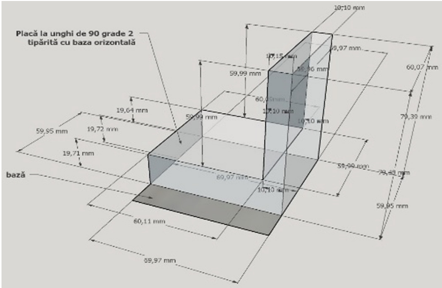

Fig. 12. Dimensions of the piece with the horizontal base

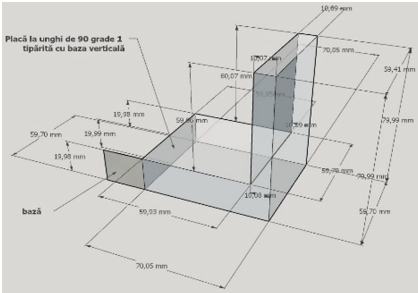

Fig. 13. Dimensions of the piece with the vertical base

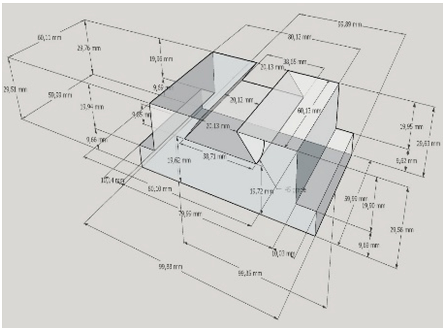

Fig. 14. The dimensions of the load-bearing part

Regarding the cubic parts with a side of 30 mm, we opted for a multiple printing, in which only the parameters of the technological process regime were modified. In total, 10 pieces with identical dimensions were printed, and in the following are the dimensional deviations of a number of 4 pieces (see Fig. 17, 18 19 and 20).

In the case of printing cube-type parts, by changing the technological process parameters (temperatures, layer thicknesses, printing speeds, etc.) not only the dimensions and reciprocal positions of the surfaces were changed, but also the quality status of the base

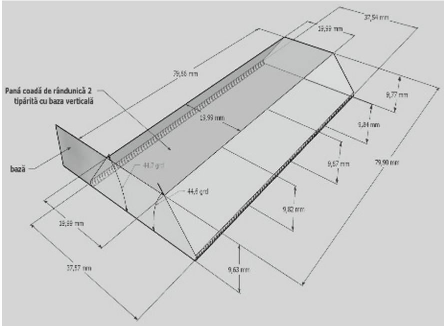

Fig. 15. Wedge piece with vertical base

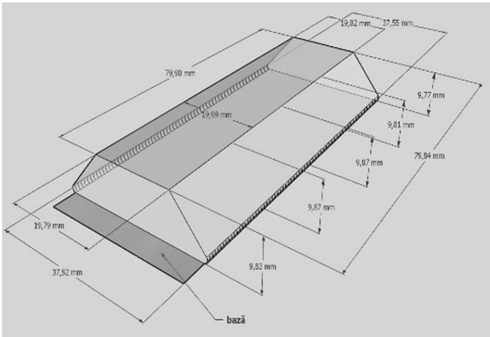

Fig. 16. Wedge-type piece with horizontal base

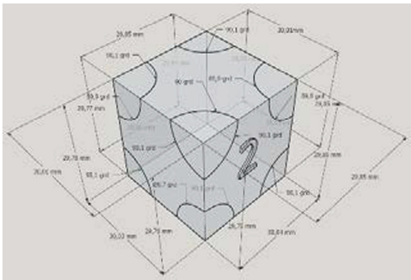

Fig. 17. The dimensions of cube no. 2

surface, the one in contact with the 3D printer platform. Thus, a series of thermal deformations appeared at the first layers, consisting of the appearance of some spaces due to the adhesion errors of the base layer. In this regard, it is found that parts no. 4 and 6 had the most stable base and adhesion to the platform. Also, in the case of part no. 10 defects in the weaving of the base layer have occurred and a series of multiple cavities are found. From the point of view of dimensions and deviations from the reciprocal

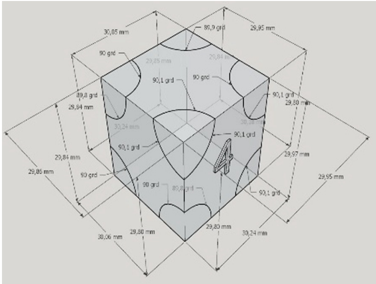

Fig. 18. The dimensions of cube no. 4

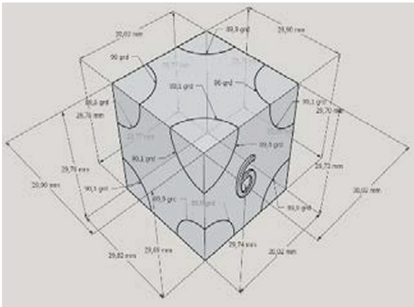

Fig. 19. The dimensions of cube no. 6

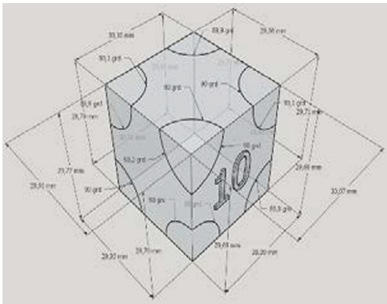

Fig. 20. The dimensions of cube no. 10

positions (angles between adjacent surfaces), it can be considered that most parts fall within the tolerance limits prescribed for CAD design.

4 Technological Process Parameters Used in 3D Printing of Parts by the FFF Process for Creality Printers

Starting from the need to determine optimal variants for establishing the technological process parameters for 3D printing by the FFF process, with the choice as material

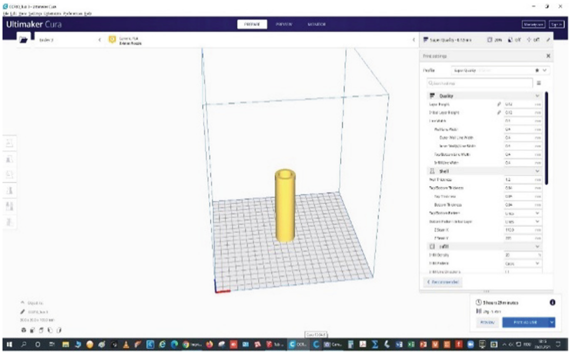

Fig. 21. Technological process parameters used for printing the tubular cylindrical part

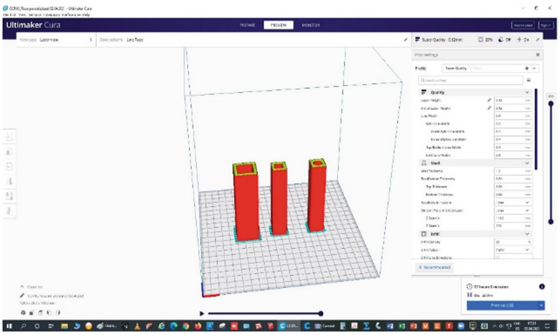

Fig. 22. Technological process parameters for printing square section conjugate parts

of the PLA filament, the limits of their variation were established, according to the possibilities of adjusting the printers used in the experimental stage. Thus, for example, in the following figures are presented a series of combinations of process technological parameters for printing the parts mentioned in the previous chapter.

Thus, in the case of the cylindrical tubular part, the parameters set in the CURA program, through which the 3D printer was ordered can be traced in the following image (see Fig. 21). In this case, the Super Quality variant was used, with a layer of 0.12 mm and a wall thickness of 1.2 mm.

For the case of conjugate parts with square section the set parameters can be observed in the following (see Fig. 22).

In the following images, printing phases can be observed on the two 3D printers mentioned above (see Fig. 23).

In order to determine the quality of the surfaces and the accuracy of the printing of the small details, measurements and recordings were made using the Bresser_Biolux_NV_20-1280X microscope. In the following images you can see details on the quality of printed surfaces, as well as measurements of the dimensional accuracy of small details (see Fig. 24).

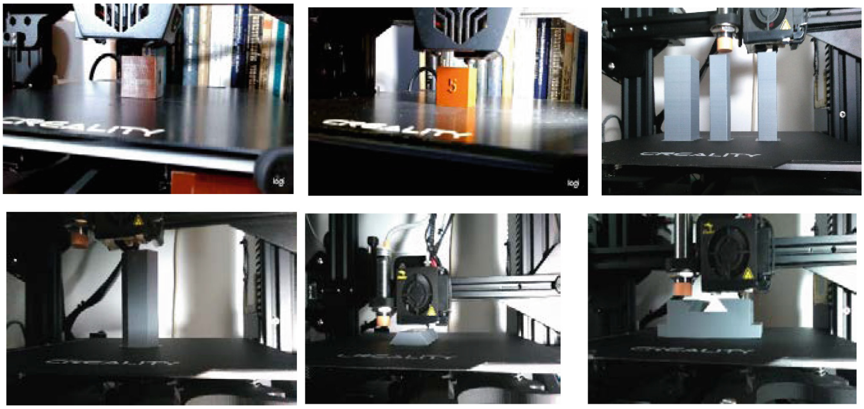

Fig. 23. Phases of 3D printing of parts by FFF technology

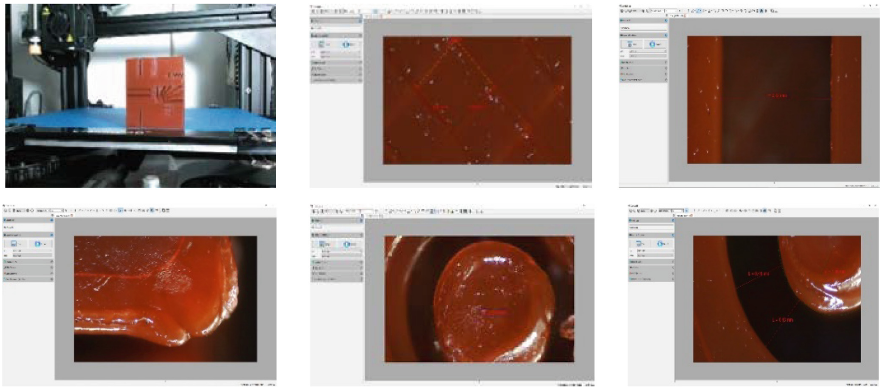

Fig. 24. Printing the part to determine the quality and accuracy of small details

Parameters for printing the cube no. 4 are shown below (see Fig. 25). The parameters that were adjusted according to the needs of 3D printing of the PLA filament had variations as follows: melting temperature, between 200 and 210 °C; printing platform temperature: between 60 and 70 °C; printing speed, between 50 and 60 mm/s; the height of the layer of deposited material, between 0.12 and 0.2 mm; the thickness of the piece wall, between 0.8 and 1.2 mm, and the density of the inner fabric, between 10 and 30%. From the dimensional and optical analysis of these parts, it is observed that the shape deviations are within the limits of permissible tolerances. The optically revealed structure of the parts (see Fig. 24) shows that the deposited layers are correctly oriented and the dimensions correspond to the requirements.

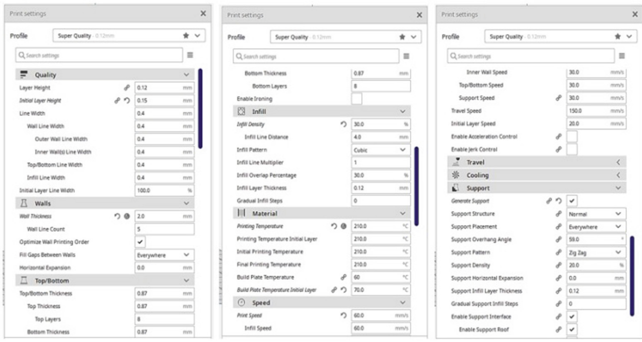

Fig. 25. Technological process parameters for printing the cubic part no. 4

5 Conclusions

Following the experimental determinations on the precision and quality of the parts made by 3D printing on printers using FFF technology, a series of conclusions can be drawn to lead to the choice of optimal technological process parameters. Thus, the thermal phenomena mentioned above, as well as aspects regarding the conformation and positioning of the parts during printing, lead to the conclusion that it is quite difficult to establish a general protocol regarding this process of making the parts. Also, due to the fact that there are a number of random external disturbing influences, such as those related to the structure and condition of the filament used in printing (eg humidity), it is often necessary to resort to testing and setting steps. of parameters by repeated tests. The data obtained regarding temperatures, printing speeds, tolerances, without claiming to be definitive, can help to choose the technological parameters of the regime, often optimal, for 3D printing.

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