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EXPERIMENTAL STUDY ON 3D PRINTED PARTS MADE OF CONTINUOUS FIBERGLASS REINFORCED POLYMER

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Abstract: *The paper is presenting studies and experiments on 3D printing of composite parts. The novelty of the printing process used is that the parts are printed using continuous reinforced fibers in a plastic matrix. Printing with continuous fiber reinforcement offers a few advantages compared to conventional processes as following: short manufacturing time, high strength, and low part weight. The internal structure of the model can be designed according to the part loads and the continuous fiber is disposed only in the layers where it is necessary. In this experimental research, an industrial part was studied and different possibilities of designing the internal structure were analyzed.*

Key words: 3D printing, CFF, fiberglass, composite materials

1. INTRODUCTION

The current market requirements are for products with high complexity. The need for weight reduction of the parts requires a process that can create more complex structures [1]. At the same time, the products should be strong enough and to be manufactured in a short time. For components with complex geometry there are not many methods of manufacturing [2, 3]. The 3D printers developed by Markforged can manufacture strong parts from innovative materials [4].

3D printing process (3DP), which is also known as Additive Manufacturing (AM), is capable to manufacture complex parts, using layer by layer principle, starting from a CAD model. At the beginning the AM technologies were used especially in the development of new products or prototypes. Currently AM technologies are widely used in different fields of industry, using different materials, in different forms (SLS, SLM, SLA, FDM) [5]. The advantages of using AM processes are: short manufacturing time of parts with complex shapes, no significant material waste and low cost of materials. [6]

FDM (Fused Deposition Modeling) technology is the most accessible and frequently used AM processes. The material, in the form of a filament, is melted and extruded through a nozzle and then it is deposited layer by layer, in the X-Y directions, until the part is finished [7, 11].

Hui et. al. studied different continuous fibers and filled structures into composites [8].

MarkForged company offers an innovative printing solution which deposits continuous fibers in a plastic matrix. They are using continuous fibers such as fiberglass, carbon fiber, and kevlar [9]. Using Markforged MarkTwo printer was obtained a strength of 700 MPa and 50 GPa stiffness in case of parts printed with carbon fibers [4]. Similar mechanical properties were obtained for parts printed with continuous carbon fibers by Anisoprint system [10].

3D printed parts with continuous fibers are used in top industry like automotive and aerospace. Wang et. al. proved that this technology is a proper solution for manufacturing composite molds [12]. 3D printed custom prosthetics or cranioplasties is another field which have a high interest [13, 15, 16].

The biggest benefit of this manufacturing technology is faster time to market. It can be used for many industrial applications such as:

clamping systems, gears, profile gauge, grippers, etc. [14, 17].

This paper aims to provide an experimental investigation focused on composites 3D printing. In this study was analyzed the effect of three manufacturing strategies on the surface roughness, dimensional accuracy, manufacturing time and costs.

2. 3D PPRINTING PRINCIPLE

FFF (Fused Filament Fabrication) is the basic principle of this 3D printing technology, in which the parts are printed from nylon or onyx as base material and can be reinforced with continuous fibers (carbon fiber, kevlar and fiberglass). During the process, the 3D printer switches between two nozzles during the manufacturing process to produce complex fiber-reinforced plastic parts. The first nozzle is used for the matrix material (nylon, in this case) and the second nozzle is for the continuous fiber. The printer has a printing bed which moves on the Z axis. This technology is named Continuous Filament Fabrication (CFF). The working principle is presented in Figure 1.

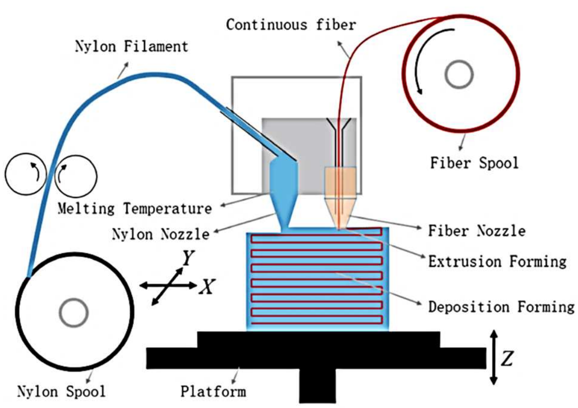

Fig. 1. CFF working principle. [8]

The effect of the fiber deposition strategy was studied according to the mechanical stresses of the parts. Eiger software is used to design the internal structure of the composite parts and allows the use of 2 continuous fiber deposition strategies. The continuous fiber can be arranged in two ways, concentric and isotropic (Figure 2a and Figure 2b) or the two deposition strategies can be combined (Figure 2c). The concentric arrangement has the shape of a spiral, which starts from the outer contour of the piece and ends inside. The rings formed by using this deposition strategy can be defined by the user, considering the surface of the part.

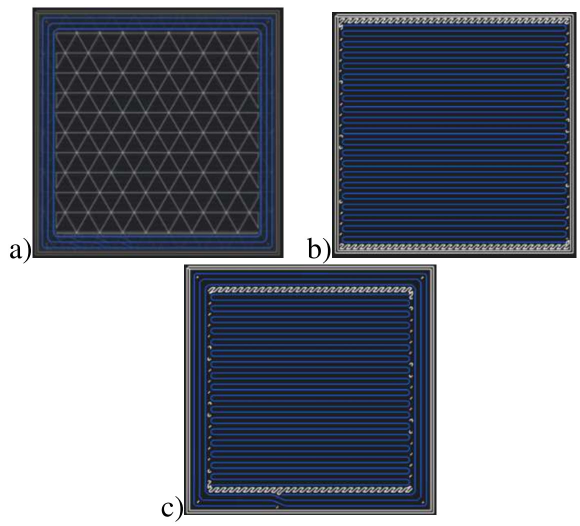

Fig. 2. Fiber printing strategies: a) Concentric fiber pattern, b) Isotropic fiber pattern, c) Isotropic and concentric rings.

In Figure 2a, the continuous fiber was arranged in 3 concentric rings. The isotropic fiber pattern consists of parallel lines and the empty areas, where there is not enough space for fiber deposition, these areas are filled with nylon.

3. EXPERIMENTAL STUDY

Using SolidWorks 2019 CAD software the 3D model of the test part was designed.

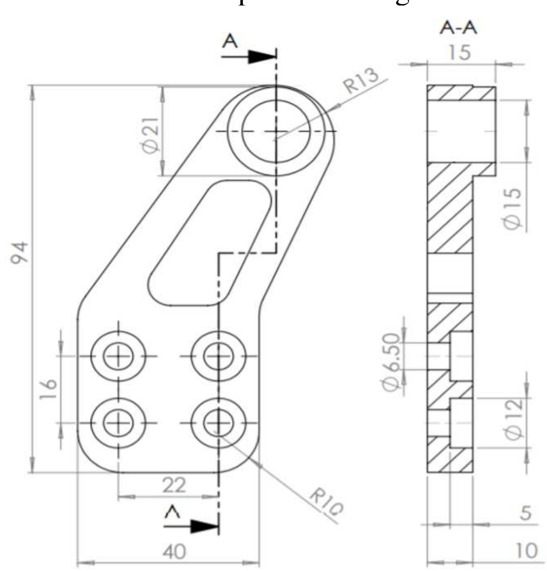

Fig. 3. Dimensions of the testing part.

The part represents the clamping system made initially by aluminium. The 3D model is shown in Figure 3.

In this experimental study a desktop printer Mark Two (from Markforged) was used as it can be seen in Figure 4. It is a CFF 3D printer and it can be used for printing with composite materials filaments, such as fiberglass, carbon fiber, kevlar and HSHT Fiberglass. Using Mark Two printer only parts with relatively small dimensions can be manufactured, the build volume being 320 x 132 x 154 mm.

Fig. 4. Markforged MarkTwo 3D printer from TUCN.

In this study, all the parts were printed with continuous fiberglass and nylon. The surfaces of 3D printed nylon white parts are smooth, do not require finishing and can be painted, if it is necessary. Nylon white is a material that can be reinforced with any type of continuous fiber. Fiberglass is a material often used to strengthen plastics because it is a rigid material, with a flexural strength of 200 MP and the selling price is reasonable. The Mark Two composite printer is capable to print continuous fiber reinforced parts, which can be as strong as an aluminum part [9].

Before starting the printing of part, it is important how to design the internal structure of the part. The Eiger software is used for placing the fiber reinforcement in the matrix. Continuous fiber layers and fiber layout strategy can also be designed. You can also choose the number of layers from the top, bottom or walls part.

In Figure 5 is presented the Eiger software with the 3D model opened. In this experimental study were analyzed three different ways of designing the internal structure of a 3D part, printed from composite materials. All the parts were printed from nylon, reinforced with fiberglass.

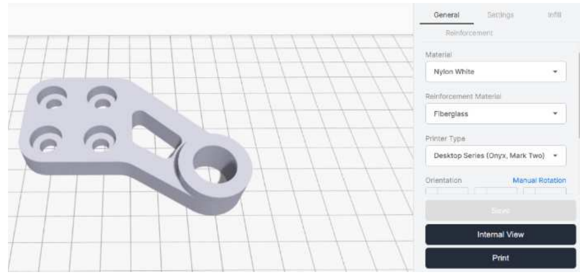

Fig. 5. STL model inserted in Eiger software.

Case study 1 (CS1) presents the internal structure of the part designed with solid fill, 100% fill density and 2 wall layers. The layer height is 0.1 mm. The reinforcement was disposed in 2 concentric rings per each layer and the total fiber layers was 8. Figure 6 presents where reinforcement is disposed inside of the part. In Eiger software it can be seen also the distribution of fiber through the height of the part. After designing the internal structure of the part and placing the fiber, in the areas where it is necessary, from the Eiger software it can be seen the approximate manufacturing time, the volume of materials, as well as the cost of materials.

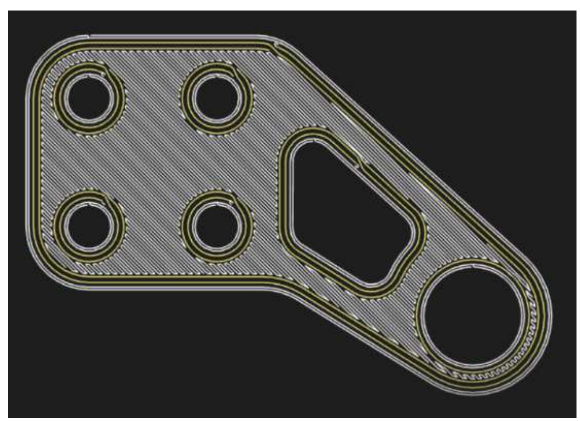

Fig. 6. Internal view of the structure design in CS1.

For this part, the fiber volume was 0.64 cm^3 and the plastic volume 21.79 cm^3. To complete the part 150 layers of materials were printed.

Case study 2 (CS2) presents the internal structure of the part was designed with triangular fill, with a fill density of 37%, 5 roof and floor layers and 2 wall layers. The layer height is 0.1 mm. The reinforcement was disposed in the same way as in the first case: 8 layers disposed in 2 concentric rings per each layer. In Figure 7 it is presented the fiberglass (with yellow) and the matrix material.

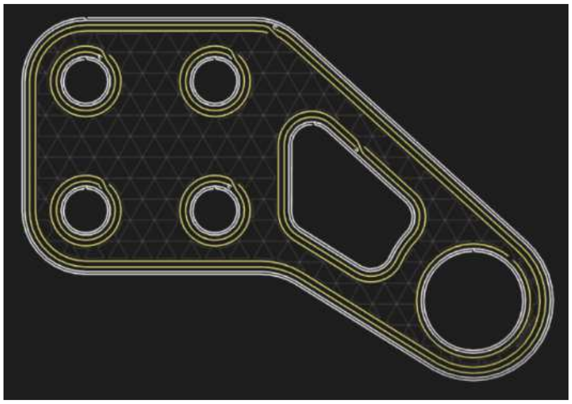

Fig. 7. Internal view of the structure design in CS2.

For this part, the fiber volume was 0.64 cm^3 and the plastic volume 13.93 cm^3.

Case study 3 (CS3) – in the 3rd case the internal structure of the part was designed with the same triangular fill, fill density of 37%, 5 roof and floor layers and 2 wall layers, as in case 2. The layer height is 0.1 mm also in this case. The fiberglass fill type was isotropic, with fiber angle: 0°, 45°, 90°, 135° and it was designed through the whole part.

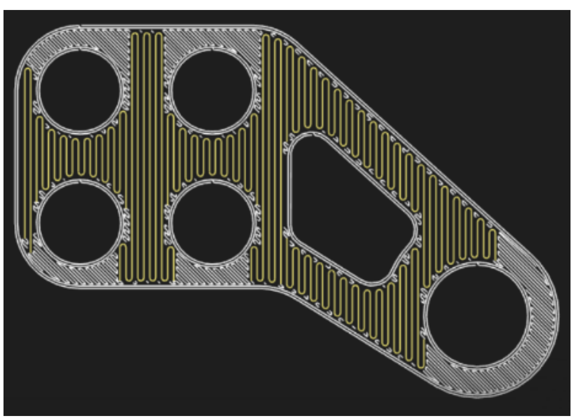

Fig. 8. Internal view of the structure design in CS3.

In Figure 8 is presented the layer where the fiber angle is at 90°. This orientation type of the fiber is not the best solution, because in some areas there is not enough space to dispose the continuous fiberglass. Due to the orientation of the reinforcing fibers, the parts do not have enough resistance to the stresses and tend to come off, under the force to which the part is loaded.

For this part, the fiber volume was 1.09 cm^3 and the plastic volume 13.92 cm^3.

Fig. 9. Printing process, using Mark Two printer from TUCN.

Figure 9 shows the CS2 part during the manufacturing. The part was printed using a triangular fill structure and fiberglass. The shape of the internal structure (triangles) has the lowest chances to deform. The parts printed with this type of parameters (triangular fill structure, wall layers number) have the advantage that can be made quickly, because the print head is moving in straight lines along the side wall. The triangular structure is recommended for printing parts due to the strength and processing speed. After manufacturing, the parts were cleaned from supports structured. An example is presented in (Figure 10).

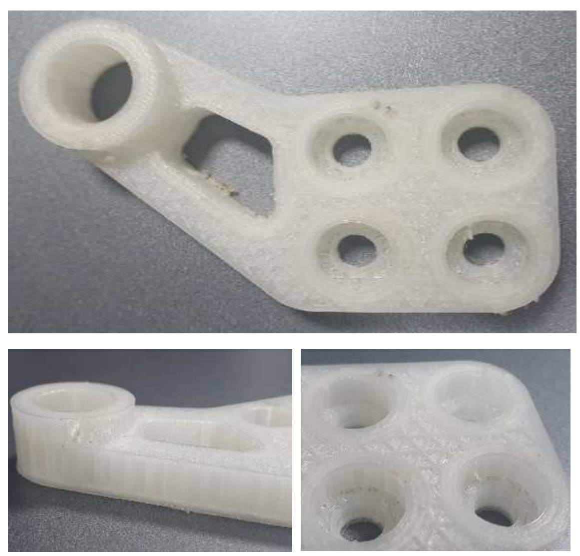

Fig. 10. The 3D part printed in case 2.

4. RESULTS AND DISCUSSIONS

To evaluate the efficiency of this 3D printing method the surface quality, dimensional accuracy, manufacturing time and costs were investigated. The values of analyzed characteristics are presented in Table 1.

Table 1

The analyzed quality characteristics based on printing strategy.

Parameters	CS 1	CS 2	CS 3
Max. external deviation, [mm]	+0.35	+0.15	+0.17
Max. internal deviation, [mm]	-0.3	-0.1	-0.13
Max surface roughness R_a, [µm]	6.8	5.3	5.5
Time, [h]	5.23	4.11	4.25
Material cost, [USD]	4.64	3.32	3.98

Dimensional accuracy was measured using a 3D measurement equipment, type Zeiss Eclipse 550. Analyzing the external dimensions, we can say that the maximum deviation between CAD model and printed parts was +0.35 mm in CS1 case, +0.15 mm in CS2 case and +0.17 mm in CS3 case.

In the case of internal dimensions, the maximum deviations are: -0.3 mm for CS1 case, -0.1 mm for CS2 case and -0.13 mm for CS3 case. The best dimensional accuracy was obtained in case of parts made without full infill (37% infill), with triangular structure.

The surface quality was measured using a Surface Roughness Measuring System SURFTEST SJ-210 from Mitutoyo. As the table shows, the highest value of the surface roughness was obtained in CS1 (R_a=6.8 µm). This sample was printed using a solid infill structure. The part made using triangular structure had a better surface quality (CS2, R_a=5.3 µm and CS3, R_a=5.5 µm).

From costs and manufacturing time point of view, the best scenario was obtained for CS2 part (3.32 USD material fee an 4h 11m processing time). To decrease the manufacturing time and costs, it is recommended to decrease the fill density, considering the technical requirements.

5. CONCLUSIONS

In this work we conclude that 3D printed technology is a proper solution for manufacturing complex parts for the industry. A nylon part reinforced with continuous fiberglass was studied, using different internal structure types. In the first case the part was designed with solid fill, 100% fill density and the fiberglass in concentric rings. In the case 2 and 3 the parts were printed using a triangular structure and 37% fill density. The difference between those 2 cases is the strategy of disposing the fiberglass. One part was printed with concentric fiberglass rings and the other one with isotropic pattern. In the last case, due to the orientation of the reinforcing fibers, the part does not have enough stress resistance.

After analyzing the test part was obtained a dimensional accuracy of ±0.15 (mm) and surface roughness R_a= 5.3 (µm).

To decrease the manufacturing time and costs it is recommended to decrease the fill density.

6. ACKNOWLEDGEMENT

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Studiu experimental privind printarea 3D a pieselor complexe, armate cu fibră de sticlă

Rezumat: În cadrul acestei lucrări sunt realizate studii si experimente privind procesul de printare 3D a pieselor din materiale compozite. Este utilizată o tehnologie de printare 3D inovativă. Noutatea procesului de printare utilizat constă în faptul ca pot fi depuse fibre de ranforsare continue, într-o matrice de nylon. Printarea 3D cu fibră continuă, oferă o serie de avantaje, comparativ cu procedeele convenționale: timp de fabricație scăzut, rezistență ridicată și greutate redusă a pieselor. Structura internă a pieselor poate fi proiectată în funcție de solicitările la care este supusă piesa, iar fibra continuă este depusă doar în straturile în care este necesar. În cercetările experimentale intreprinse s-a studiat o piesă cu o geometrie complexă și au fost analizate diferite posibilități de proiectare a structurii interne.

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