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INFLUENCE OF THE DIRECTION OF PARTS MODELING BY POLYMER DEPOSITION ON THEIR STRENGTH

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Abstract. *This paper presents the results of a survey to determine the resistance of parts prototyped in different directions by Fusion Deposition Modeling, in order to make allowances to product designers choose the appropriate position for the modeling of parts. Specimens were made for tensile and flexural tests, modeled with overlapping layers in the longitudinal direction and in the thickness direction. The results showed that CPs with overlapping layers in the longitudinal direction had broken at lower stress than CPs with overlapping layers in the thickness direction. Therefore it is important to define the orientation of the model so that it has adequate strength for its function.*

Keywords: *3D printing; Prototyping; FDM; Fused Deposition Modeling*

1. INTRODUCTION

This paper presents the results of a survey to determine the tensile and flexural resistance of parts prototyped in different directions by "Fusion Deposition Modeling" (FDM), in order to make allowances to product designers choose the appropriate position for the modeling of parts using the Dimension Elite equipment.

The results of a profound study about the anisotropic material behavior, under tensile and compression, of fused deposition modeling ABS is presented by "Sung-Hoon Ahn, *et al*., 2002". There it can be learning the influence of the trajectory of the printing head (raster orientation) on these properties. The authors found that air gaps inside the material and raster orientation have great influence on the strength of the prototyped model.

A study about stress strain behavior of prototyped models was undertaken by "Bellini and Güçeri, 2003". The experimental results were used to build the tensors and to perform a finite element analysis of prototyped material. They also found that the strength of prototyped material is lower than this solid material.

In this work a brief introduction about "Fusion Deposition Modeling" is presented addressing process, modeling and the influence of staking layer orientation on the resistance of the prototyped model.

The experimental part had been consisted of tensile and flexural tests. Specimens for tensile and flexural tests had been printed with overlapping layers in the longitudinal direction and in the thickness direction. The specimens had been produced using the best quality of the FDM equipment.

A discussion about the influence of the orientation of the model for printing is presented based on the results of the experiments.

2. FUSION DEPOSITION MODELING (FDM)

Fusion deposition modeling is an efficient tool to generate physical prototypes from virtual 3D models. These models can be used as tools by designers to evaluate and improve new products. This technique permits to print products such as pack the orientation of the model so that it has adequate strength for its function aging, insulated products like hangers, set of parts that can be assembled and disassembled, and mechanical systems. Fusion deposition shortens modeling time and need less resources for producing physical models than the manually produced, which in many cases are not functional. It also avoids spending of financial resources that would be used for expensive molding tools and production pilots for processes like injection of thermoplastics. FDM is a fast prototyping technique to obtain physical models to be tested in a few hours. The physical properties of the prototypes provide a wide range of applications for testing geometry, ergonomic assessments, evaluations aerodynamics in wind tunnels and assembly. "Figure 1" shows few products printed by FDM at PRO-SME laboratory.

Figure1. Products printed by FDM at PRO-SME laboratory.

A review about rapid prototyping techniques was presented by "Upcraft and; Fletcher, 2003", "Volpato, *et al.*, 2007" and "Gibson, I., et. al, Additive Manufacturing Technologies, 2010".

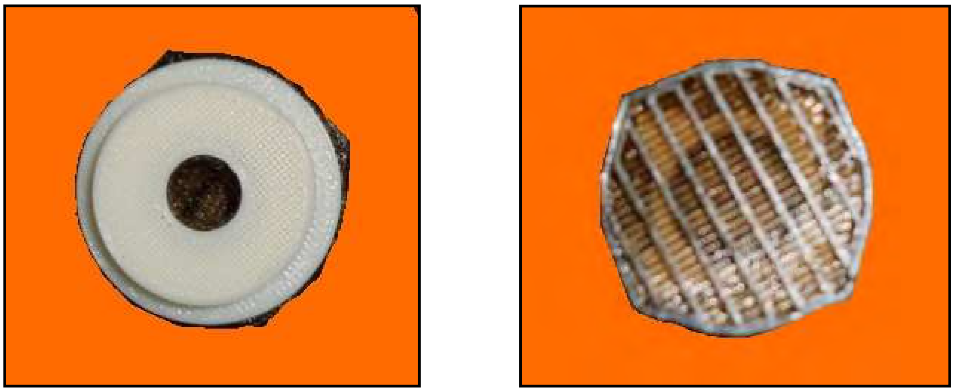
2.1 The FDM process

In the FDM molding process the prototype is build layer by layer. Each layer is molded by the deposition of filaments of melted polymer in a tray, according to a trajectory generated by the software of the machine. The material of the prototype, thermoplastic polymer, is heated in a cylinder head up to the extrusion temperature and then flow through the hole forming a filament.

The deposition of the filament is made in each layer in XY orientation by the movement of the mechanism that supports the extrusion head. The trajectory of this head is created by the software of the machine from a 3D model file of the part to be molded.

After each layer molding, the tray undergoes a vertical displacement of a previously set distance for the next layer thickness.

For this process it is necessary to have a holder material to support the first layer of the model and to fill its voids. After the printing process, the holder material is removed from the model by physical or chemical (solvent) means. A picture of a model before the support material removal is presented in "Fig. 2". In "Fig. 2(a)" the support material can be seen inside the hole (void) of the model and in "Fig. 2(b)" on the back of the model.



(a) (b)

Figure 2. (a) The support material in the hole (void) of the model and (b) on the back of the model.

2.2 Modeling for prototyping by FDM

This process has as its starting point the modeling the piece to be prototyped using a CAD/3D. This software permits to export a file from 3D model in "*.STL" extension, which will be recognized by the software for prototyping. In this software the user is able to define some parameters, such as:

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- The orientation of the model relative to the tray;
- The thickness of each layer of material to be deposited;
- The fill type for the model (solid, high density or low density).

After the parameters selection, the software slices the virtual model in several horizontal and plan layers limited by the contour of the model at the height correspond to each layer. Each slice contains the information where the material of the model must be laid and where are the voids, which must be filled with backing material.

The contour lines define the profile of each layer, and inside the contour the layer is filled with cross slanted filaments. The pattern of the filaments is called raster. The sequence of layers in the vertical orientation (Z axis) forms solid model. The thickness of the layers is obtained by the vertical movement of the tray of the machine.

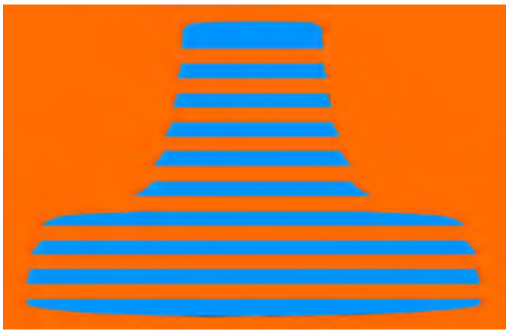
2.3 Influence of staking layer orientation on the resistance of the workpiece.

During the formation of a layer carries an extrusion head of material that is deposited over the previous layer and directed in the XY plane according to the programmed path. This plan in formed by filaments of polymer in which exists a large molecular alignment in its longitudinal direction given by the motion of the extrusion head. This molecular alignment causes great resistance of the polymer in this direction due to the alignment of the covalent bonds.

Polymers for FDM are thermoplastic and therefor the bond between molecules, the Van der Waals type, is weak and up to ten times lower than the covalent bond. The layers are connected by this type of bond and the connection force depends on how efficient is made the fusion of the previous layer caused by the deposition of the hot filament. For an efficient connection, it is necessary to have mixture of molecular chains from both layers. Some polymers for FDM have additives to improve the bonding between layers.

The bonds between molecules, inside and between layers, in FDM technique, suggest that the orientation chosen for the virtual model is extremely important because it will define the direction of the superposition of the layers. Therefore, direction of the model with major the strength will be the ones inside the layer and it will be chosen by the orientation of the virtual model. Figure three presents a model and two options for layers orientation.

(a)



(b)

(c)

Figure 3: (a) Model, (b) model with overlapping layers on vertical direction and (c) with overlapping layers on horizontal direction.

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It is expected that the strength of the model with overlapping layers on vertical direction is greater in horizontal direction, inside the plane, than in vertical direction and the opposite occurs with model with overlapping layers on horizontal direction.

3. EXPERIMENTS TO DETERMINE THE INFLUENCE OF THE MOLDING DIRECTION ON TENSILE AND FLEXURAL STRENGTH OF PROTOTYPED MODELS

The tests had been undertaken on standardized specimens printed with overlapping layers in the longitudinal direction and specimens with overlapping layers in the thickness direction.

The work piece material was"P430 ABS Model" (white) and the support material was "P400 Soluble Support" (black). These materials are provided in cartridges by the printer manufacturer.

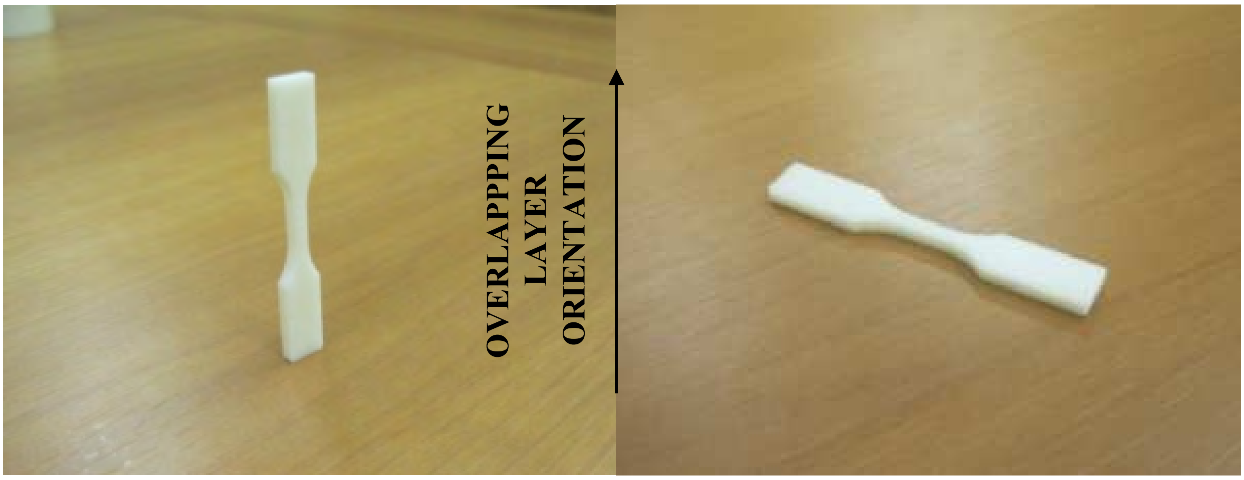
The specimens have been modeled in a 3D software and printed in a Dimension Elite FDM printer, produced by the American company Stratasys. The models were exported as a '*.STL' file and read by the Catalyst software that was used to choose the printing parameters. The following parameters had been chosen for the specimens printing: solid refill (option for denser body); thickness of 0.254mm and orientation of layers for each type specimen. The raster orientation, paths followed by the printing head to mold the layer, in this work were generated by the software of the FDM printer. For each layer the machine prints the contour of the specimens and fills them with diagonal filaments displaced +/- 45 degrees from the axis of the specimens. The same strategy for raster orientation was used to print all specimens for this research.

Seven units of each type specimen have been printed for the tests and they were identified according to the overlapping layers orientation.

The tensile and bending tests were carried out in a Universal Machine for Mechanical Tests Instron, model 5562, equipped with force transducer for loads up to 10 kN, located in the Laboratório de Ensaios Mecânico (LAPTEC 2) of the Institute of Macromolecular Professor Eloisa Mano (IMA/UFRJ). The sensor of this equipment is connected to a computer for data acquisition, which was also used for data processing.

3.1 Tensile tests.

The specimens for these tests had been modeled according to ASTM D638 Type V. “Figure 4” shows the specimens printed with overlapping layers in the longitudinal direction and in the thickness direction.



(a) (b)

Figure 4 – (a) Specimens printed with overlapping layers in the longitudinal direction and (b) in the thickness direction.

Measurements of the thickness and height of the useful part of the specimens have been undertaken at three different points. “Figure 5” shows a picture of the tensile tests set-up.

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Figure 5. (a) Tensile test set-up and (b) detail of the specimen fixed by the pneumatic claws.

"Figure 6" shows the graphs Stress x Strain plotted with data from the tensile tests with the two types of specimens. The graph from tests with specimens with overlapping layers in thickness direction, displays a behavior expected for a plastic material while the graph for the specimens with overlapping layers in the longitudinal direction displays a fragile behavior.

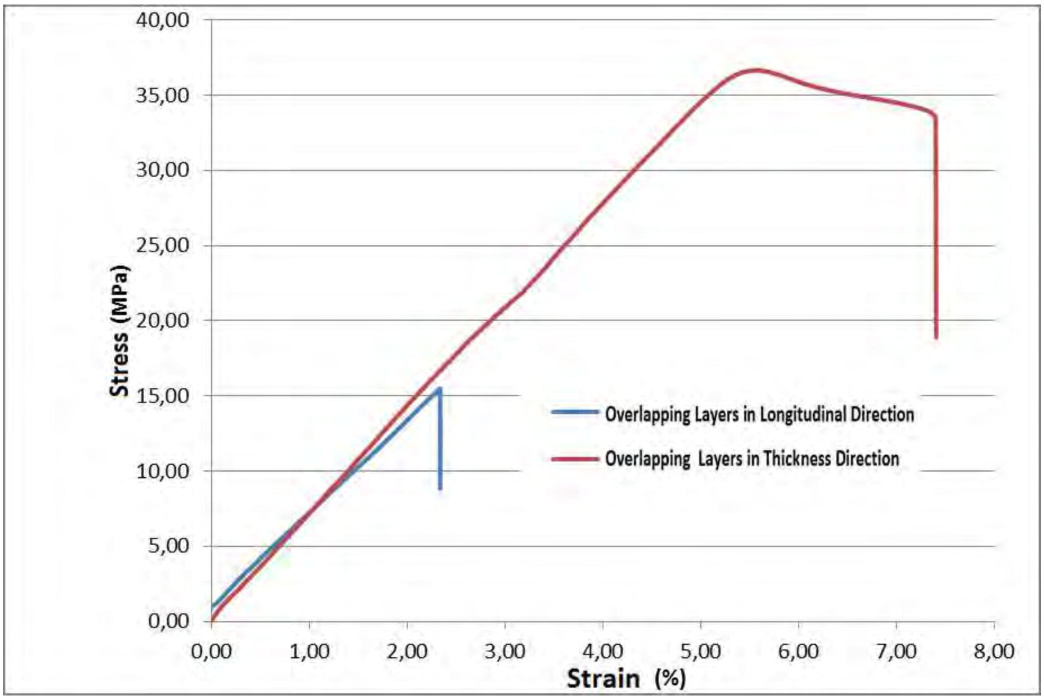

Figure 6. Graphs Stress x Strain plotted with data from tensile tests with the two types of specimens.

"Tables 1 and 2" shows the results of tensile tests with both types of specimens. The values were obtained by statistical treatment of the data from the tests with the seven specimens of each type.

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Table 1. Results of tensile tests for specimens with overlapping layers in the thickness direction.

Values	Stress at maximum load (MPa)	Strain at maximum load (%)	Yield Stress (MPa)	Strain at Yield (%)	Young Modulus (MPa)	Stress at the break (MPa)	Strain at the break (MPa)
Graph	36.68	5.59	36.68	5.59	718.8	33.49	7.40
Average	36.86	5.72	36.87	5.72	743.0	32.54	7.64
Standard Deviation	1.16	0.80	1.17	0.80	57.1	1.35	1.06

Table 2. Results from tensile tests with specimens with overlapping layers in the longitudinal direction.

Values	Stress at maximum load (MPa)	Strain at maximum load (%)	Yield Stress (MPa)	Strain at Yield (%)	Young Modulus (MPa)	Stress at the break (MPa)	Strain at the break (MPa)
Graph	15.47	2.34	15.47	2.34	671.7	15.47	2.34
Average	16.34	3.18	15.89	3.08	642.2	15.82	3.22
Standard Deviation	1.83	0.58	1.76	0.61	26.2	1.62	0.66

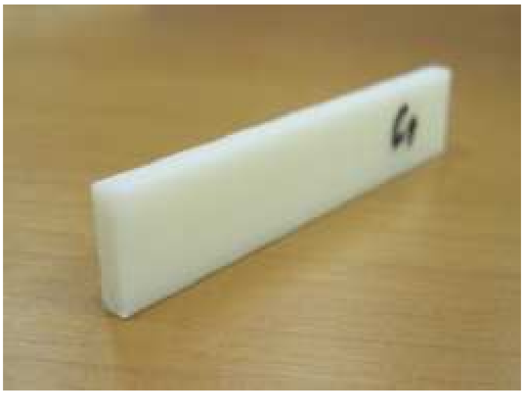
Comparing the values of maximum stress and breakdown stress for both types of specimens it is possible to conclude that the specimens whose layers were superimposed in the direction perpendicular to the thickness have twice the strength with which the superimposed layers lengthwise. These results are inside the range of 32 to 45 MPa found in "Sung-Hoon Ahn, *et al*., 2002" work.

The elongations of the specimens at break point were also different. The specimens with the molding of the layers in the longitudinal direction showed an elongation of less than about 32% of the value found for the specimens with the molding of the layers in thickness.

These results suggest that when layers are overlapped in the thickness direction, the material of the specimens displayed a ductile behavior and high resistance and when the layers are overlapped in the longitudinal direction exhibit a brittle behavior and low resistance. This conclusion can be confirmed by the graphics and the appearance of the spots where the fractures occurred.

The graph with results from tests with specimens with overlapping layers in the thickness direction had large deformation in the outflow region before fracture while the other rupture occurs abruptly after the elastic region of the graph.

The specimens with overlapped in the longitudinal direction showed a brittle fracture after breakage while the specimens with overlapping layers in the thickness direction showed a ductile fracture, as shown in figures 7 (a) and (b).



(a)

(b)

Figure 7. Fractures lands of the specimens with overlapping layers in the (a) longitudinal and (b) thickness directions.

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3.2 Flexural tests.

For this experiment standardized specimens were printed with overlapping layers in the longitudinal direction and specimens with overlapping layers in the thickness direction.

The specimens for flexural tests had been molded according to ASTM D790 and have their widths measured in the center.

The bending tests had been also performed with the same equipment used for tensile tests with the specimens being bi-supported and with the load applied at its center.

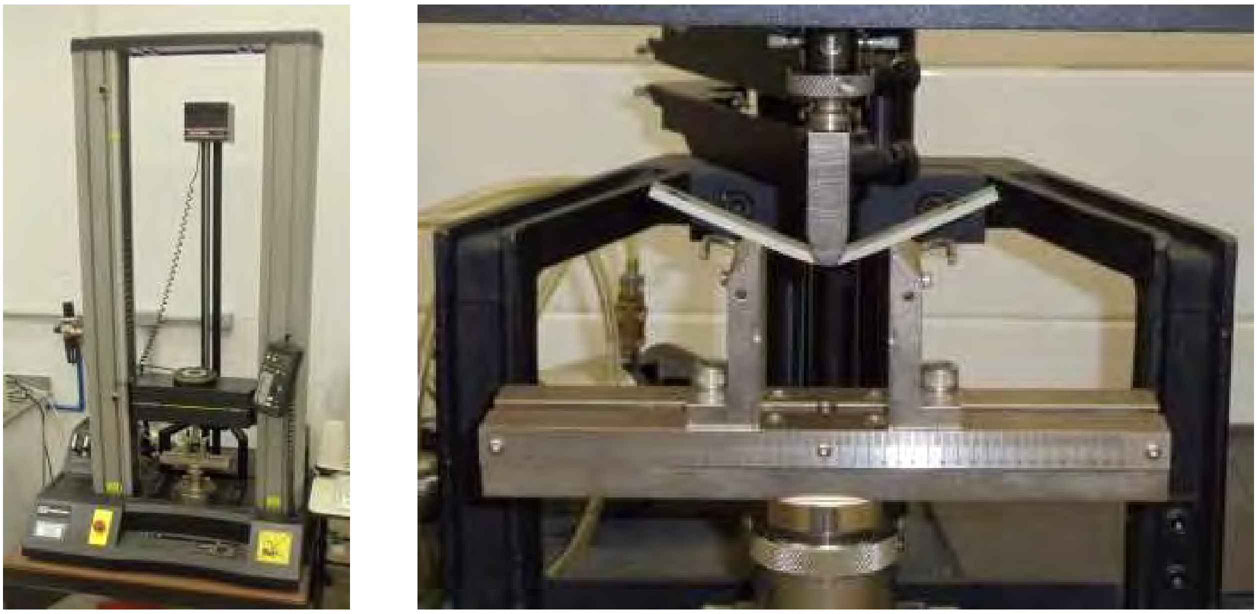

Figure 8. Experimental set-up for bending tests.

"Figure 9" Shows the graphs Stress x Strain plotted with data obtained during the bending test for both types of specimens.

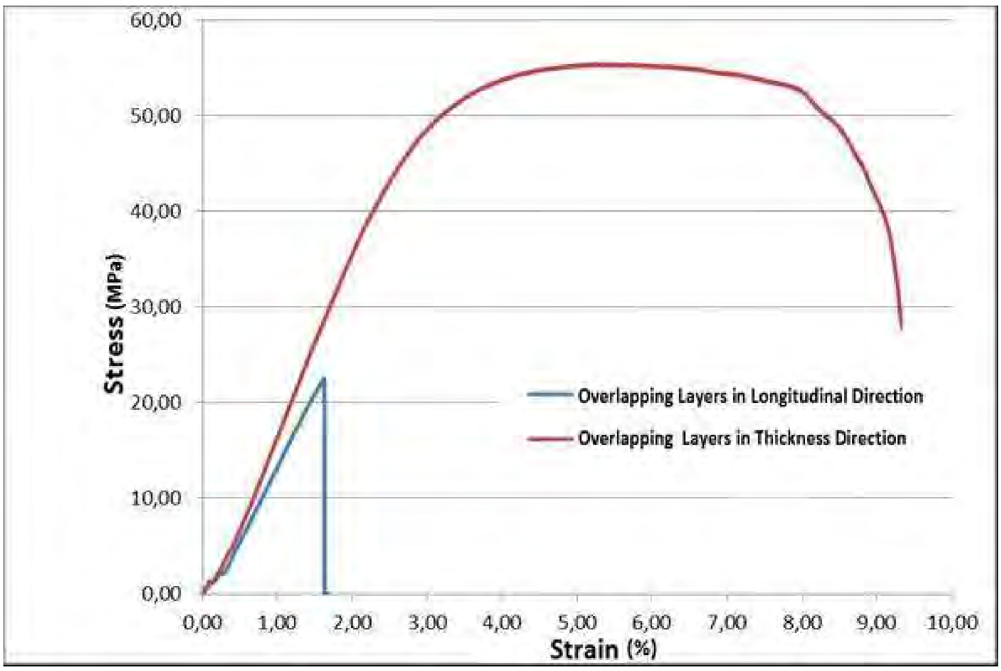

Figure 9. Graphs Flexure Stress x Strain plotted with data from bending tests with both types of specimens.

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"Tables 3 and 4" show the results obtained from the bending tests. The values were obtained by the same statistical treatments made with the results obtained in the tensile tests.

Table 3. Results of bending tests for specimens with overlapping layers in the thickness direction.

Values	Stress at Maximum Load (MPa)	Strain at Maximum Load (%)	Yield Stress (MPa)	Strain at Yield (%)	Young Modulus (MPa)	Stress at the break (MPa)	Strain at the break (MPa)
Graph	55.44	5.30	55,44	5.30	1948	52.59	7.98
Average	54.76	5.40	54.76	5.40	1916	52.38	8.02
Standard Deviation	2.31	0.20	2.31	0.20	112.2	2.18	0.17

Table 4. Results from bending tests with specimens with overlapping layers in the longitudinal direction.

Values	Stress at Maximum Load (MPa)	Strain at Maximum Load (%)	Yield Stress (MPa)	Strain at Yield (%)	Young Modulus (MPa)	Stress at the break (MPa)	Strain at the break (MPa)
Graph	22.57	1.60	2.38	0.30	1585	22.57	1.62
Average	22.67	1.70	17.83	1.40	1540	22.48	1.72
Standard Deviation	1.23	0.14	10.38	0.70	68.00	1.11	0.14

The value of the maximum stress for the specimens with overlapping layers in the longitudinal direction were approximately 40% lower than those found for the specimens with overlapping layers in the thickness direction.

The values of strain at break of the specimens with layers in the longitudinal direction were approximately 20% smaller than the strain at break of the specimens with layers in the thickness direction. The behavior of the specimens with overlapping layers in the longitudinal at the break had been more brittle than the behavior of the other type of specimens and it is consistent with the behavior observed at break of the tensile specimens.

4. DISCUSSION

The results from the tests are consistent with the hypothesis of the anisotropic strength of models produced by FDM. The anisotropy appears to be caused by the molecular structure of the molded polymer. In thermoplastics polymers the bond inside the molecules are covalent while between the molecules are weak forces of the type Van der Walls, what decreases the overall strength of the polymer. Moreover, the filament molding process is extrusion that causes molecular orientation what contributes for the increase of the rigidity and strength of the material in its direction. The bond between layers is caused by a re-fusion near the surface of the previous layer. This type of bonding does not provide molecular orientation between layers and makes difficult to have an efficient mix of molecules from both layers. Therefore, the weak linking bond force is predominant between layers and they are easily broken when under traction, what can explain the fragile behavior of the material in this direction. On the other hand, the molecular orientation inside the layer aligns the strong covalent forces what increases the polymer strength. In This case, at the beginning of a tensile test the molecules inside the layer are stretched. After that, sliding between the molecules, inside and between layers, takes place due to the breakage of some weak forces. Finally a general breakage of all links of the molecules occurs. The sliding phase can explain the ductile behavior of the specimens with overlapping layers in thickness direction.

Rigid and with thick wall products ("Fig. 2") may not be affected by the anisotropy but flexible products probably will. Plastic connectors, such as presented in "Fig. 10", are products where flexion of two beams occurs to permit the clamp and release. The flexion of the beans happens during the movement for connection of the two parts and after this movement the beams are released and must return to its original position to clamp the connector.

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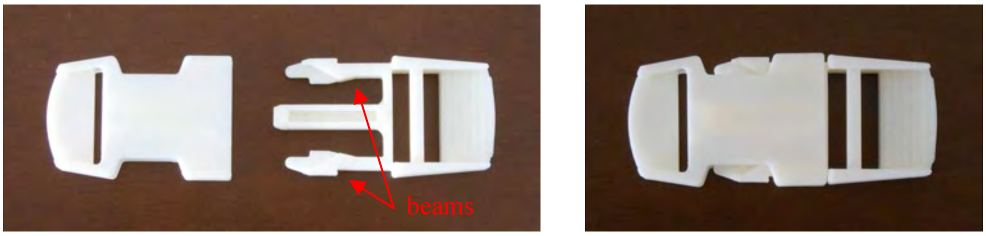
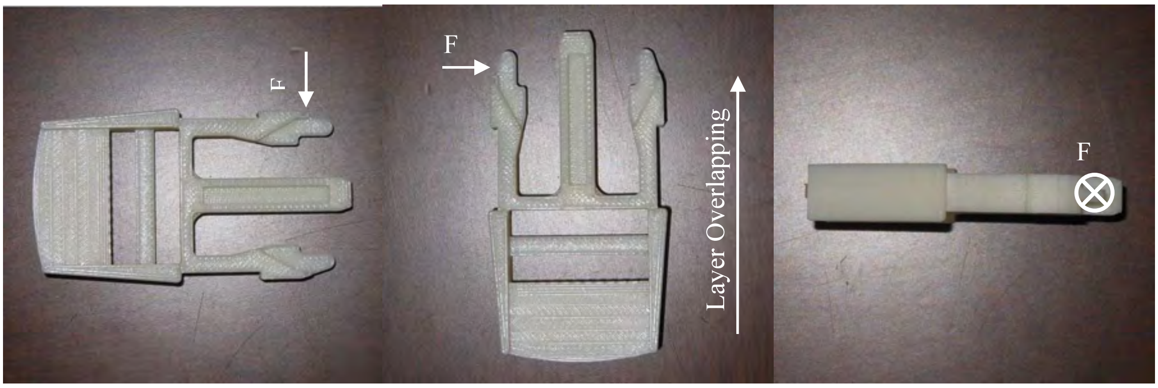


(a) (b)

Figure 10. Connector (a) open and (b) clamped.

The deflection of the beams cause stresses from traction in its outer part and from compression in its inner part. If the stresses caused by the deformation of the beam are greater than the yield limit for its material, it will not return for its original position after the release of the load. If the stresses caused by the deformation of the beam are greater than its breakage limit it will breaks during the movement for connection of both parts. Based on this behavior of the beans and the results of the tests, the quality of the connector is highly dependent of the overlapping orientation of the layer. “Figure 11 presents tree different positions of the beams connector for the same overlapping layer orientation.



(a) (b) (c)

Figure 11. Three different positions of the beams connector for the same overlapping layer orientation.

In “Figs (a) and (c)” the force that causes the beam deflection is applied perpendicular to the plan of the layers, and therefore, also perpendicular to the direction of the filaments. It makes that these positions for printing are excellent because the stress caused by deflection will be resist along the filament. On the other hand, in the connector oriented as shown in figure (b), the stresses caused by the force must be resisted by the week bond between the layers (filaments), what makes it a poor choice for the overlapping layer orientation. Forces that will cause failure of the connector printed as in “Fig. (b)” will not break connectors printed as in “Figs (a) and (c)”.

Based on the results of this work it can be said that before start the prototyping process by FDM it is necessary to know the direction of the stresses in the model during its use to choose its best orientation for printing.

5. CONCLUSION

A brief introduction about “Fusion Deposition Modeling” was presented addressing process, modeling and the influence of staking layer orientation on the resistance of the prototyped model.

Tensile and flexural tests had been undertaken with specimens printed with overlapping layers in the longitudinal and in the thickness direction. The results from both types of tests showed that specimens printed with overlapping layers in the thickness direction are about two times stronger than the ones printed in the longitudinal direction.

The specimens with overlapped in the longitudinal direction showed a brittle fracture after breakage while the specimens with overlapping layers in the thickness direction showed a ductile fracture.

Based on the results of the experiments, a discussion about the influence of the orientation of the model for printing was presented. The conclusion was that it is extremely important to define the orientation for the overlapping layer direction of models so that it has adequate strength for its function.

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