EXPERIMENTAL STUDIES OF MECHANICAL BEHAVIOR OF FDM RAPID PROTOTYPED PARTS

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Abstract. *Rapid Prototyping systems are becoming more flexible and efficient providing new ways ofdeveloping product in the engineering field. However, little information about rapid prototype process system parameters or mechanical behavior of prototyped parts is available. The aim of this paper is to provide some data about mechanical properties of FDM parts, in order to help engineers and designers to better use their equipments. Two types of tests were carried out, tensile strenght and torque tests. The anisotropic behavior of prototyped parts is under investigation and some different building parameters were evaluated with tensile strength test. Some conclusions were made about the relation between adjacent filaments and strength; possibility to increase torque resistance by infiltrating liquid bonder. The results showed that Policarbonate(PC) prototyped parts are almost twice as strongt asacrylonitrile butadiene styrene (ABS) parts.*

Keywords*: Rapid Prototyping, FDM, tensile strength, torque.*

1. INTRODUCTION

1.1. Context

Rapid prototyping is a manufacturing technology that has been receiving a strong attention lately. Its application encloses several industrial segments, such as medical, automotive and aerospace area (Fraunhofer, 2006; Gimm, 2004; Wohler, 2003; JTEC/WTEC, 1997; Jacobs, 1980). This technology consists in building a 3D component from a CAD model in a short period of time. The model is "sliced" and built layer by layer up on special machines (Cimject, 2006; Gimm, 2004).

Rapid Prototyping systems are becoming more flexible and efficient providing new ways of engineering. Earlier use of RP was restricted to prototype fabrication in product development processes (Gimm, 2004). The introduction of new materials and systems make possible to use the parts for functional tests or to produce end-products with low demand (Stratasys, 2006; Gimm, 2004). But little information about system parameters or mechanical behavior of prototyped parts is available (Borille *et al.*, 2005; Bellini *et al.*, 2004; Thrimurthulu *et al.*, 2004; Sun *et al.*, 2003; Ahn *et al.*, 2002; Anitha *et al.*, 2001).

The aim of this work is to provide some information about mechanical properties of FDM parts, verifying the influence on tensile strength and torque of different construction parameters.

1.2. Definitions

Fused Deposition Material, or FDM, is a Rapid Prototyping technology which consists of a nozzle that extrudes a thermoplastic polymer filament. A head supports the nozzle and moves on an X-Y coordinate system while the filament is deposited on a base until the CAD-defined profile at the current layer is completely filled. Then, the base moves a distance equivalent to a layer thickness downward and the nozzle begins to extrude a new layer.

Some definitions are necessary for an appropriate understanding of the FDM building process, parameters and its influence. These are described below and presented on Figure 1.

Layer thickness: thickness of each CAD model's slice.

Road Width: width of each filament extruded by the nozzle to fill each layer.

Air Gap: distance between the limits of adjacent extruded roads.

Road Direction: angle between the extruded filaments and the direction of tensile load at the tensile strength test. The layers were built alternating the road directions in 90º. For example, the -45ºx45º road direction means that the filaments of the first layer were extruded with an angle of -45 degrees related to the direction of tensile load at the tensile strength test, the second layer with an angle of 45 degrees, the third layer -45 degrees and so on. At 0x90 º, the half of the filaments is aligned to the traction direction (0 º) and the other half is perpendicular.

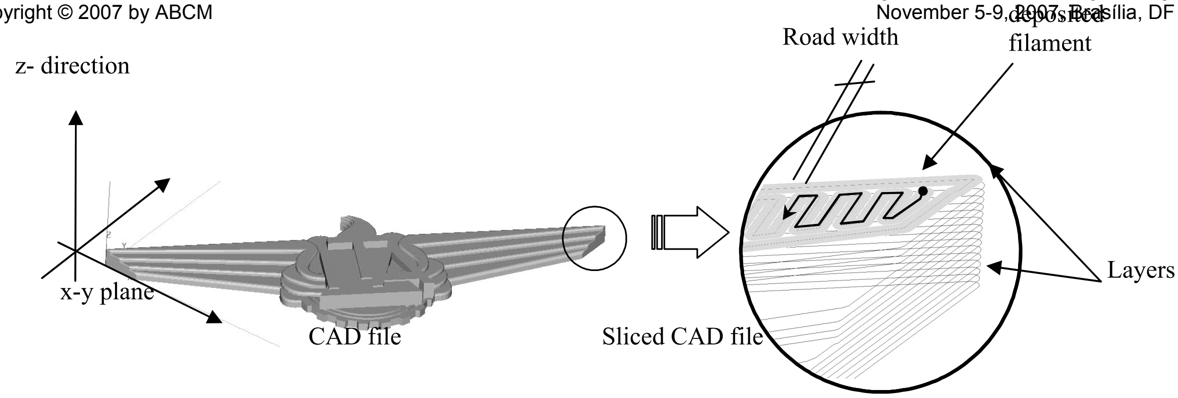

Figure 1. FDM process parameters

2. EXPERIMENTAL METHODOLOGY

2.1. Methodology

To improve the knowledge about system parameters and the mechanical behavior of parts produced utilizing FDM, two main tests were carried out, tensile strength and torque tests. The anisotropic behavior of prototyped parts is under investigation and some different parameters were evaluated with tensile strength test.

2.2. Tensile Strength

These tests were divided in three steps. The first one (Tab. 1) was conduced to evaluate the influence of the road direction (related to tension direction) and the layer thickness. The parameter group which presented the best performance regards Tensile strength at the first step was selected to verify the influence of road width (second step, Tab. 2). The third step (Tab. 3) has evaluated the behavior of parts built with different air gaps.

Table 1. Tensile test, first step parameters.

Parameters	A	B	C	D
Air gap/overlap [mm]	0	0	0	0
Layer thickness [mm]	0.1778	0.1778	0.254	0.254
Road direction [º]	0x90	-45x45	0x90	-45x45
Road width [mm]	0.3048	0.3048	0.4064	0.4064

Table 2. Tensile test, second step parameters.

Parameters	E	F	G
Air gap/overlap [mm]	-0.0254	0	0
Layer thickness [mm]	0.254	0.254	0.254
Road direction [º]	-45x45	-45x45	-45x45
Road width [mm]	0.4064	0.6564	0.9564

Table 3. Tensile test, third step parameters.

Parameters	H	I	J
Air gap/overlap [mm]	-0.0254	-0.0508	-0.127
Layer thickness [mm]	0.254	0.254	0.254
Road direction [º]	-45x45	-45x45	-45x45
Road width [mm]	0.9564	0.9564	0.9564

The values presented in the tables have been selected from preset list in machine software (Insight™). The relation layer thickness/road width was fixed as close as possible for these tests due to the dependence between the layer thickness and the road width values in the software.

For each condition, five 3.3 x 25.4 x 229 mm rectangular specimen were built according to ASTM D3039 (ASTM, 1976). The orientation in machine envelope has been maintained constant. The specimen are shown in Fig. 2. For these tests, only Acrylonitrile Butadiene Styrene (ABS) parts were evaluated.

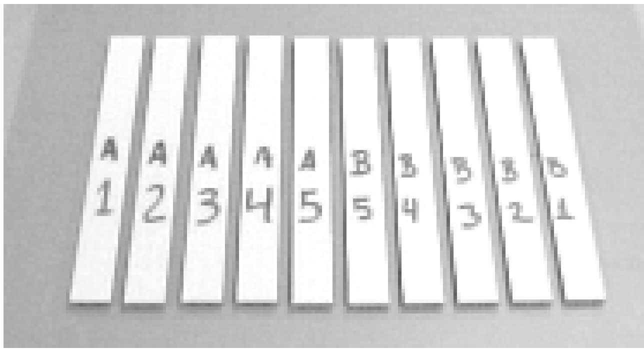

Figure 2. Tensile tests specimens

2.3. Torque

This test intends to compare the maximum torque supported by prototyped acrylonitrile butadiene styrene (ABS) and Policarbonate (PC) parts under different building orientations. The test consists into applying torque on the screw until it promotes the failure of the plastic part thread.

The geometry and screw were selected from industrial applications. They represent geometries used for mold injected parts at an automotive industry for fixture systems. The aim is to compare ABS and PC prototyped parts.

Since the anisotropic behavior of prototyped parts was under investigation, the specimens were built in four different orientations, as showed in Fig. 3 and Tab.4, utilizing the same 0.254 mm layer thickness (machine default building parameters).

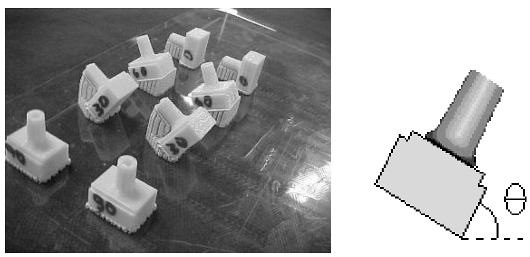

Figure 3. Torque part and building orientation.

Table 4. Building parameter for torque tests.

Condition	Orientation θ (º)
1	0
2	30
3	60
4	90

2.5. Equipments

Two FDM machine were used for specimens building, Titan and Dimension from Stratasys®, and utilizing the softwares Insight 4.0™ and Catalys 3.0™.

The tensile properties were measured using an EMIC Universal Testing Machine, according to ASTM D3039 standard.

The samples images were taken with a Zeiss Stemi SV11 stereoscopy.

The torque measurements were carried out utilizing Digital Mackena, Model MK-210.

3. RESULTS AND DISCUSSION

3.1. Tensile Strength results

The results for the first step tests are shown in Fig. 4. It can be observed a little improvement at tensile strength for thicker layers (conditions C, D and E). In addition, no relation was found due to part location on the machine table. This implies in a well established machine temperature control during process while building these parts.

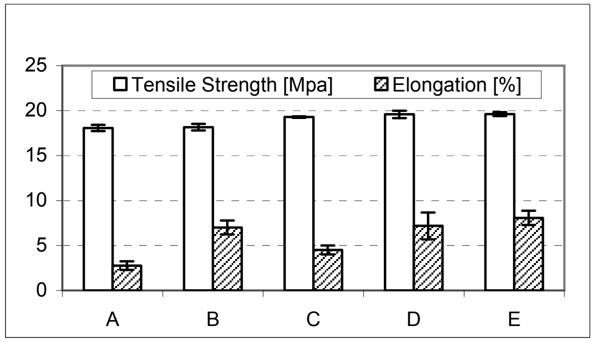

Figure 4. Comparison between different build parameters.

For the same layer thickness with different road directions (conditions A-B or C-D), no substantially difference was noted upon tensile strength. However, at -45x45º road direction (conditions B, D, E), the elongation was higher than 0x90º (conditions A, C). It can be concluded that at -45x45° an accommodation of the filaments at the load direction occurs. This displacement leads to a higher elongation before the total failure (Fig. 5).

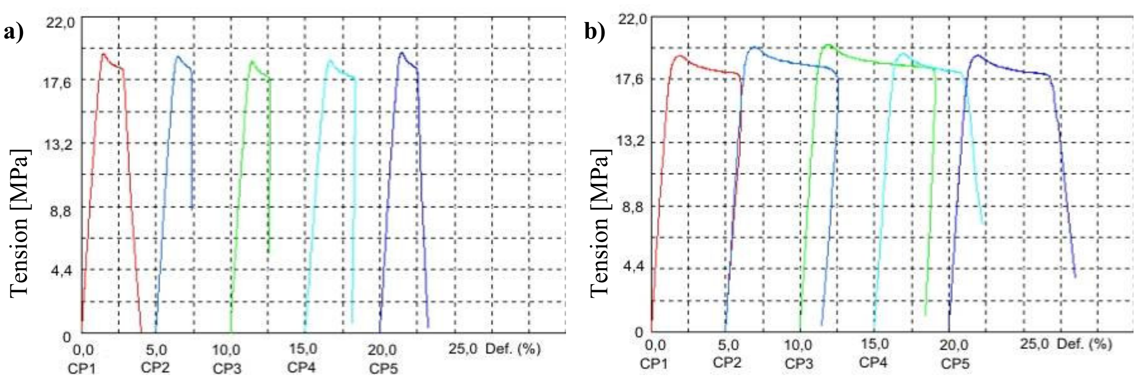

Figure 5. Tensile X deformation graphic: road direction a) 0x90° b) -45x45°.

From the results above, we can suppose that the roads at -45x45° tend to align themselves with the load direction. Consequently, the filaments can support the tension for higher deformations. At 0x90°, a little deformation separates the adjacent filaments (the filaments at 90° in relation to traction direction), overcharging the filaments at 0°. These filaments can not sustain the mechanical load and collapse.

The condition D (Tab. 1) was selected to test the road width influence on tensile strength and elongation because it showed a higher tensile strength. The results related to conditions E, F, and G (Tab. 2) are presented on Fig. 6.

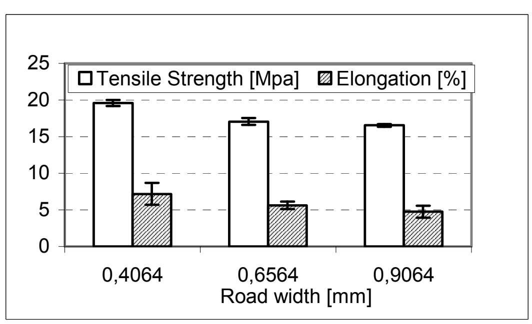

Figure 6. Road width influence.

The results showed that increasing the road width, the mechanical behavior does not have the same effect as increasing the layer thickness. That is, for thicker layers, the tensile strength is improved, while for higher road width it seems that the opposite occurs.

In order to better observe the phenomenon, stereoscopy images were taken of the parts surface. It can be noticed from Fig. 7 that the larger roads do not have been successfully formed, leaving gaps between filaments as a consequence.

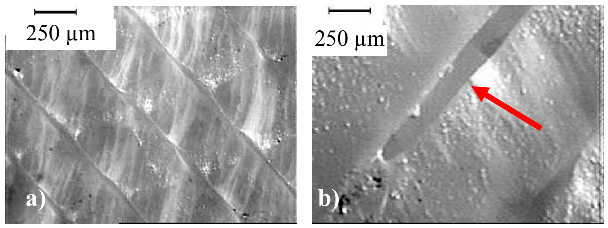

Figure 7. Prototyped surface with thin (a) and large road (b).

A higher feed filament deposition velocity is necessary to create a larger road. Probably, the higher velocity causes a deformation over the previous layer (Fig. 8).

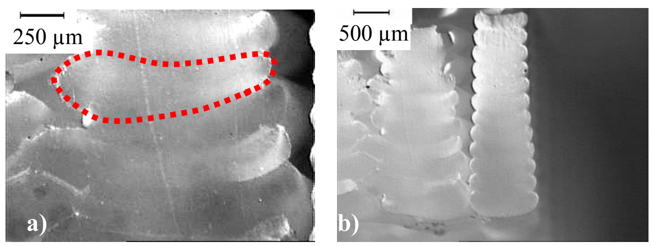

Figure 8. Deformed layers on larger road widths

This layer deformation causes a bad layer filling and decreases the interface adhesion between filaments.

Considering that the decrease of tensile strength was due to the poor adhesion between adjacent layers, an evaluation was carried out in order to promote a better material deposition. Three probes were built (step 3 - tests H, I and J) with a overlapping of filaments. As the filaments seem to be poor bonded laterally due to an existing distance between them, a reduction of the theoretical distance of the filaments boundaries by the machine software was performed. The software parameter for the distance between adjacent deposited roads is the air gap.

The Fig. 9 shows that an overlapping between the adjacent filaments improved the tensile strength, with a corresponding reduction on elongation.

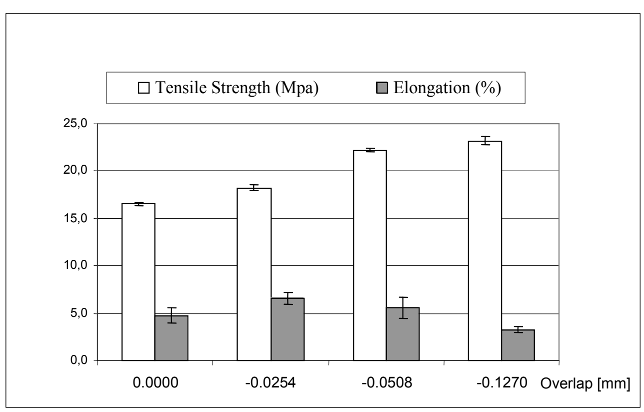

Figure 9. Deposition overlap influence on tensile strength and elongation on FDM built parts.

Nevertheless, an excessive overlapping had a negative influence on surface finish and probe dimensions, as it can be seen in Fig. 10 and read in Tab. 5.

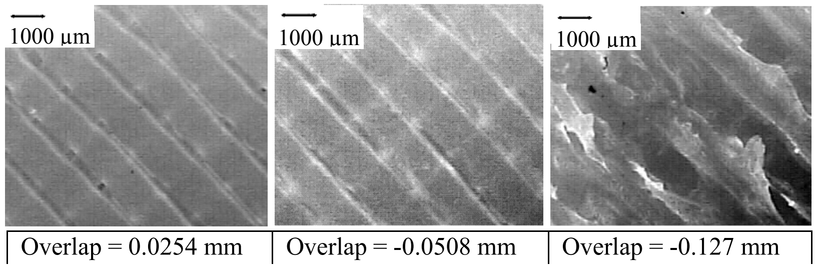

Figure 10. Surface texture of tensile strength tests parts.

Table 5. Dimensional measurement of tensile strength tests parts.

Test	Measured		Modeled (theoretical value)	
	Width [mm]	Thickness [mm]	Width [mm]	Thickness [mm]
H	25.39	3.4	25.4	3.3
I	25.37	3.4		
J	25.69	3.88		

3.2. Torque results

In ABS specimens built with the first condition (0º- Tab. 4) presented a fracture before the screw could be totally placed. In some applications that could be impossible to build such features at other orientations, a possibility to overcome such a problem is using the capillarity effect presented by FDM parts. Due to the deposition process, parts built at FDM machine present gaps between adjacent filaments, thus, this characteristic leads to the liquid absorption behavior.

Although it is not the aim of this work, in order to demonstrate this phenomenon some tabs were build and one extremity of each tab was introduced in a recipient with blue drawing ink. The blue ink was selected due its low viscosity and to provide visibility through the tabs (Fig. 11).

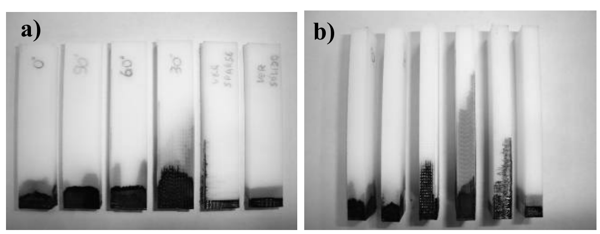

Figure 11. Capillarity effect on FDM parts.

This effect may be useful or not. For example, FDM parts cannot be directly used as reservoir or fluids ducts. Therefore, a blender or glue, such as cyanoacrilate can be used to reinforce the internal body structure. The distribution behavior of penetrated liquid is not the aim of this work, but, its necessary further studies. For now, it is enough to know that the capillarity effect was present at all building conditions.

With the intention of avoid this premature fissure (Fig. 12a), and utilizing the capillarity behavior presented by FDM parts, a glue (AMBROID PRO WELD) was deposited in a new specimen and a subsequent test was carried out. The Fig. 12b shows the improvement obtained with this method, and the torque tests results are presented in the following table.

Table 6. Torques tests results.

Orientation θ [º]	ABS [N.m]	PC [N.m]
0	0.6(*)	1.4
30	0.7	1.5
60	1.2	1.8
90	1.0	2.0

(*) the part was infiltrated with a bonder.

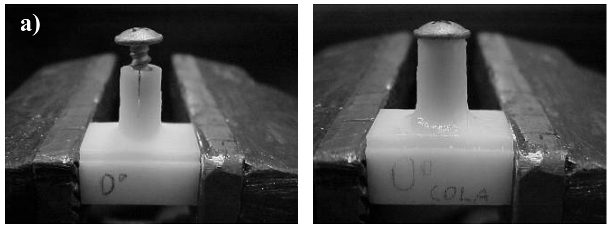

Figure 12. a) Premature fissure, b) reinforced part.

The new specimen did not present the premature failure. The glue filled the gaps between the filaments providing a better resistance for this part.

Observing the results, Polycarbonate parts obtained a better performance in comparison with ABS bodies. None of the PC bodies presented this fracture in any of the tested conditions, but in a certain moment of the tests the thread just failed.

Other important behavior was the relation between torque and orientation. The torque strength rises with the increase of the orientation angle (θ). It can be understood, because the strength of the screw on the hole wall is in a axial direction, i. e., trends to enlarge the hole. As the interfaces between the layers are the weakest regions of the FDM parts (as can be seen on Fig. 11a), the failure occurs between the layers interface), the torque resistance increases with the orientation angle (θ), because the layers are at the perpendicular direction meaning the strongest orientation related to axial stress.

4. CONCLUSIONS

In order to provide some information about the FDM process some mechanical tests were carried out. It can be concluded that the interfaces between adjacent filaments are a weak region of the FDM parts. With this assumption, for higher resistance FDM parts, the largest road and the dicker layer shall be used. It should also be used an overlapping between adjacent roads. In this work, the overlapping distance of 5% of the roads width proved to increase the resistance while 13% has negative effect to surface quality. From Tensile X Deformation graphs, it can be concluded that the filaments at 45 degrees (in relation to tension load) have longer deformation before they failure.

The interfaces between filaments promote a capillarity effect. It may be used to infiltrate a liquid bonder material in order to increase resistance. It was shown with a torque test, where a screw could not be fixed in some conditions without the application of a bonder material. Also, the torque resistance of prototyped parts depends on the building orientation in the machine. The torque resistances of PC parts were almost twice compared to ABS parts.

The building parameters affect the deposited filaments uniformity that can cause mechanical properties loss. Since the FDM parts properties are anisotropic, a special attention is needed when choosing the process parameters in order to achieve better mechanical properties

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