3D PRINTING WITH NATURAL FIBER REINFORCED FILAMENT

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Abstract

An initial study of 3d printing with compound filament using different plastic matrices and sugar cane bagasse as the filler was conducted. In order to do this, a reverse engineering process was made to several 3d printer extruders to determine how to change the extruder in order to be able to print with the filament. To obtain the filament, a plastic extruder was modified to obtain a compound filament of 1.75 mm using a 3x4 design of experiments with the factors percentage of fiber (10% 20% 30%) and type of matrix(PE,PP,ABS,PLA). The filaments obtained were tested to determine the mechanical properties and finally were used in a 3d printing to compare results.

Introduction

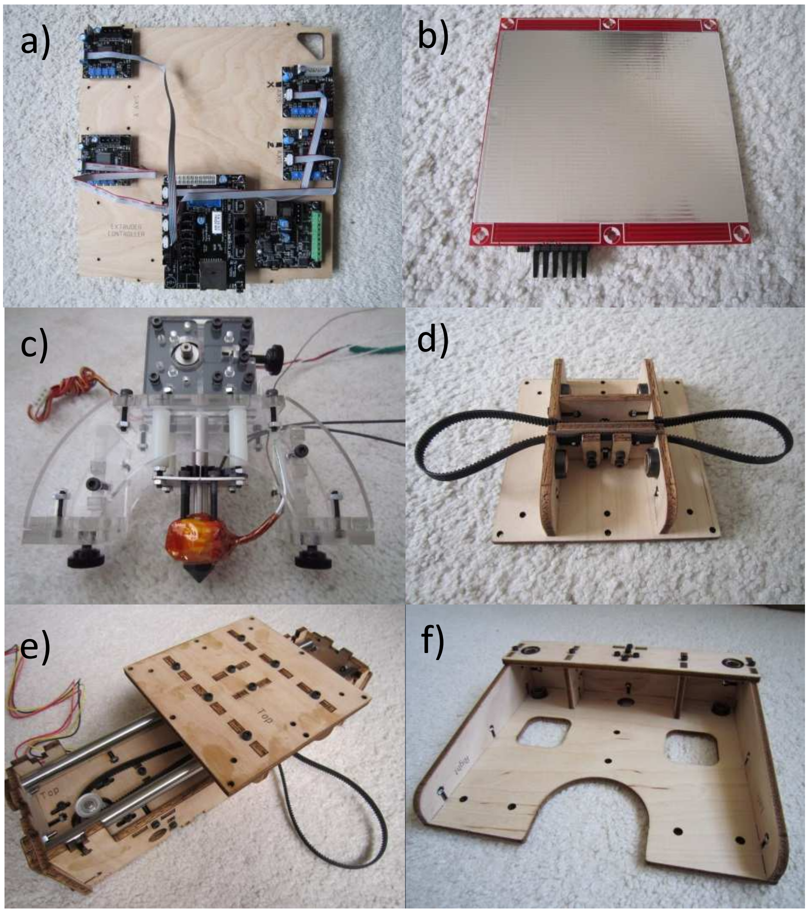
Additive manufacturing technologies have the advantage over traditional technologies to produce fast, flexible and competitive parts, prototypes, molds, dies, or custom end products directly from digital information[1]. Additionally, they have the advantage of reducing product development times, and most importantly fabricate designs and features unmatched by other methods of manufacturing[2].The downside of the pieces obtained by rapid prototyping technologies are that the products obtained do not have the same mechanical properties than those obtained by traditional manufacturing processes. Additionally, the filament used in the process is not locally produced or distributed in Colombia, making the prices of the process higher for massive use. The proposal is to study the fabrication of a natural fiber reinforced composite of thermoplastic matrix reinforced with natural fibers, a combination that has shown in other applications to have higher mechanical performance than when using only the thermoplastic material [3], and investigate their application in the field of rapid manufacturing, specifically for Fused Deposition Modeling, FDM. To this, a design of experiments for the material was made, the material was mechanically characterized, and a reverse engineering process of some additive manufacturing equipment was made.

Materials and Methods

Reverse Engineering

The starting point for this research was the process of reverse engineering to a FDM 3d printing machine. The machine chosen for this process was a 3d Thing-o-Matic printer. This was a pioneer in the field of low-cost 3D printers from the Makerbot company, whose dimensions are approximately 30x30x40 cm, with a build area of approximately 0x10x10. This printer was one of the first fully automated commercial 3D printers, by software all printing parameters can be controlled, and once the print begins, no human intervention is required until the process ends. This makes it a machine suitable for the process of reverse engineering, well it is very complete, and additionally low cost.

Reverse engineering is a systematic process of dismantle where it is intended to list the problems and design opportunities, and to disassemble, measure and analyze the modules or operational subsets, to extract a list of primary functions, and components related to each functions, to understand operation. Figure 1 shows some of the functional subassemblies of the machine.

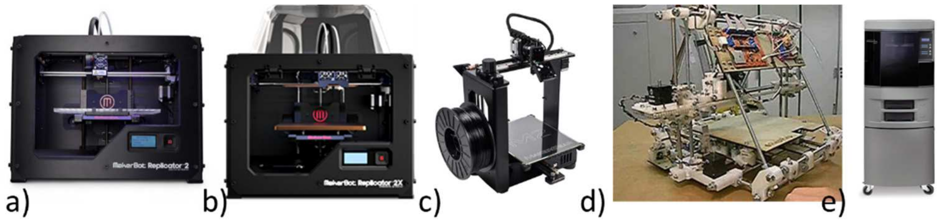


a) Control System b)Hot Platform c)Extruder d)X axis Mechanism e) Y axis Mechanism and f)Z axis mechanism.

Figure 1. Functional Subsets of the Commercial Thing o Matic printer.

After the reverse engineering process, functional subsets were identified. In order to generalize the common functions for 3D printers, a similar process was also realized with other 3D as shown in Figure 2, and although the reverse engineering process was not applied completely, it served as a reference point for identifying these functional subsets. The printers chosen range in price, quality and brand, such as Stratasys Dimension 1200es, which is a professional industrial printer whose market value is around thirty thousand dollars, and the Mendel Prusa, an amateur kit for hobbyists whose cost is around six hundred dollars. Other printers are in the medium range, about two thousand dollars each, but widely use in the growing industry of personal 3D printing.

After realizing the reverse engineering process, and experimenting with the referenced machines, the following subsets where identified: structure or framework, positioners in each of the axes X, Y and Z, one printing platform extrusion mechanism and a control system.



a) Makerbot Replicator 2 b) Makerbot Replicator 2x c) Makergear d) Prusa Mendel e) Stratasys Dimension 1200es

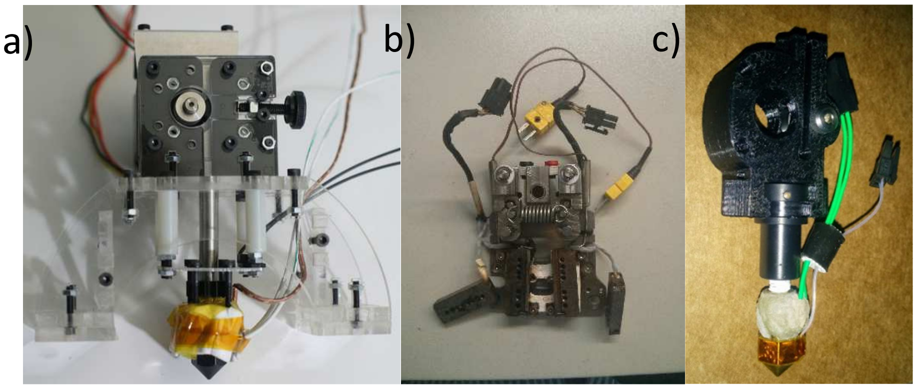
Figure 2. Reference 3d Printers.

Generally, the majority of printers have a steel structures with calibrated axes used as guidelines for the displacement in each axis of motion. Additionally, pulleys and belts are used to transmit movements in the x and y plane, and worm gears are used for lifting the platform in the z axis. Extrusion mechanisms vary from one machine to another, as some are single headed while others are double, some have the motor directly coupled to the toothed pulley feeding the filament, while others have a gear system, and operating temperatures for the head range between 25 and 300 °C. The platforms generally have temperature control for printing with ABS, and the materials of these platforms can be plastic, metal or glass. Table 1 list the functional subsets identified in the machines studied.

Structure	Structure
	Filament Support
	Hot Plate
Movement Mechanism	X Axis
	Y Axis
	Z Axis
Extruder	Filament Speed
	Temperature Control
Control	Electronics
	Motors
	Firmware and Software

Table 1. Functional Subsets in 3d printers.

Since the main goal of this research was to use a NFRC in FDM printing, the extruder head or printing block of most of these printers was also studied using the reverse engineering process, to clearly identify its functions and components and be able to learn based on the knowledge gained from existing machines. In Figure 3 the extruder blocks used in the study are shown.



A. Thingomatic. B. Stratasys. C. Makergear.

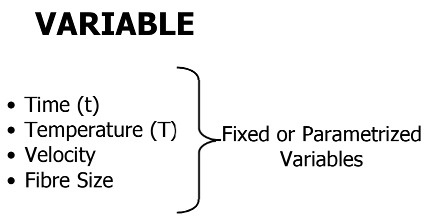
Figure 3. Reference Extruder Blocks.

After realizing the reverse engineering process to each of the heads in order to obtain a better understanding of them, the functional decomposition begins. Initially the head is visualized a whole, both inputs and outputs for the system are determined, and summarized in a black box diagram. Then the functional decomposition show the relationship between functions in order to transform the input into the output. The general functional blocks for all the printers studied are showed in figure 4.

Figure 4. Functional Subsets in Extruders.

<u>Design of Experiments</u>

The design of experiments methodology was used in order to determine the significance of the fiber volume fraction and the matrix used, in the physical and mechanical properties. Figure 5 shows design of experiments used.



3 X 4 Design			
F2 \ F1	C1	C2	C3
PE	C1-PE	C2-PE	C3-PE
PP	C1-PP	C2-PP	C3-PP
PLA	C1-PLA	C2-PLA	C3-PLA
ABS	C1-ABS	C2-ABS	C3-ABS

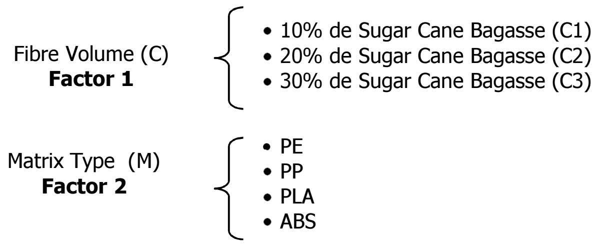


Figure 1. Design of Experiments

In order to obtain the 1.75mm in diameter filament to be used in a 3d printer, an extruder must be used. An old extruder used to make plastic hose was modified and reconditioned in order to obtain the filaments. After the conditioning of the machine was done, the composite fabrication process started. The polymeric matrixes were obtained in pellets, and the natural fiber used was obtained pulverized with the help of SENA, Astin Center. The filament was manufactured in the plastic transformation Lab of the GITEM investigation group at Universidad Autonoma de Occidente. Figure 6 shows the process of obtaining the filament. The proper quantities of matrix and filament where weighted and manually mixed, to be feed into a HOT PLATE PRESS where a standardized cycle was used in order to apply controlled temperature and pressure to homogenize the composite. The output of this process was a rigid board which was then pelletized in a mill, and then feed to the extruder in order to extrude the filament.

Figure 6. Filament fabrication process.

This process turned out to be the most important for the design of experiments because of the experimental validation that in order to obtain a good filament, other additives and chemical treatments must be used for a successful extrusion. Additionally, to obtain an homogenous material, a twin screw extruder must be used, and thanks to the conclusions of this project, it was requested and will be used in future investigations.

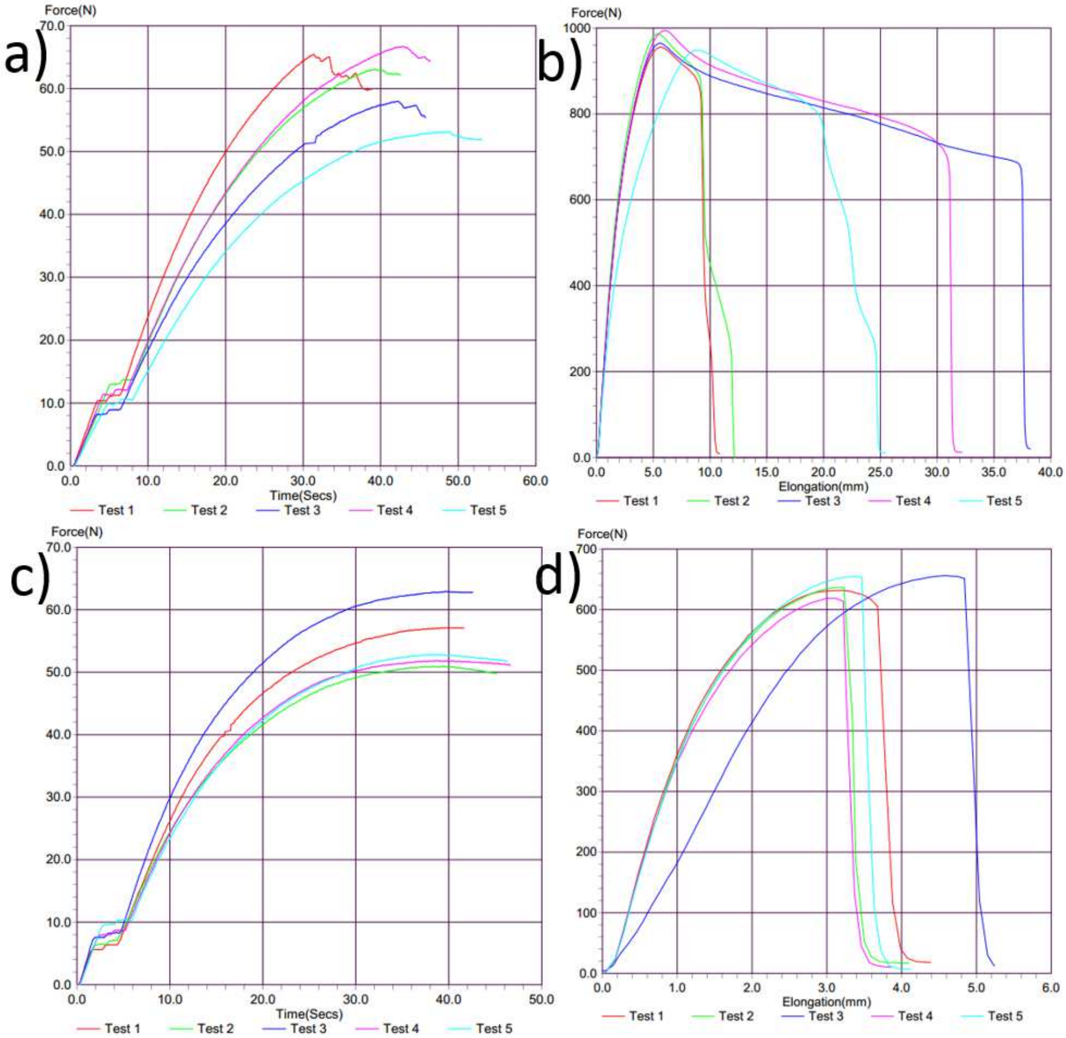
Table 2 shows the summary of the design of experiments for the extrusion process. Extrusion property refers to the ability to get the filament out of the nozzle of the extruder, speed refers to the speed with which the material is allowed to pull to reduce its diameter after leaving the nozzle, and fragility relates how fragile is the filament obtained.

		Fiber Percentage %			
Matrix	Property	0%	10%	20%	30%
PE	Extrusion	Yes	Yes	Yes	Yes
	Speed	Medium	Low	NO	NO
	Fragility	Low	Low	-	-
PP	Extrusion	Yes	Yes	Yes	Yes
	Speed	High	High	Medium	Low
	Fragility	Low	Low	Low	Medium
PLA	Extrusion	Yes	Yes	Yes	Yes
	Speed	Medium	Low	No	No
	Fragility	High	High	-	-
ABS	Extrusion	Yes	No	No	No
	Speed	Medium	-	-	-
	Fragility	High	-	-	-

Table 2. Extrusion Results.

When trying to extrude the ABS, very brittle filament was obtained. The literature review revealed that commercial ABS filaments ranges between 75% and 90% ABS, and the remainder is a co-polymer of styrene and acrylonitrile (SAN) and dyes or other additives which increase the ductility which reduces fragility[4][5]. Similarly, for the PLA it was also found that the percentage composition ranges from 85% to 90% polymer and the remainder are additives which improve its properties[6][7]. PP and PE are not widely used for 3D printing as they are very flexible and its adhesion properties are not very good [8]. Moreover, their shrinkage coefficients are much greater than those of ABS and the PLA [9], which produce deformed parts with design measurements deferring from final parts. However, these materials are easily extruded, and it can be observed that when increasing the percentage of fibers, extrusion speed must be slowed in order to obtain filament. The literature research also explains this as increasing fiber content increases the brittleness of the composite [10] and decreases if ductility.

Afterwards, it was observed that the mixture of PP with 20% sugarcane bagasse was the composite which best behaved at the time of extrusion, and in agreement with the ASTIN- SENA, and the Laboratory of Physical Tests polymers, physical and mechanical tests were performed to determine their behavior. Annex B shows the results of the tests conducted, five samples of each compound of polypropylene, which further were chemically treated to try to better adhesion of the fibers to the matrix. Figure 7 shows a summary of the test, where it can be observed that the fibers are working as filler and not as reinforcing agents well pure polypropylene properties are better than the compound.



A) 3 point Flexion PP B) PP Tension. C) 3 point Flexion PP-20% Bagasse D) Tension PP- 20% Bagasse

Figure 2. Mechanical Flexion and Tension Results.

Manufacturers and sellers of fiber-reinforced composites recommend not to print with nozzles less than 0.5mm diameter [11][12][13]. An experimental setup where the filament obtained was printed in air until a steady flow without changes in the output was obtained was performed. It was tested with nozzles of 0.4mm, which is the standard nozzle used for printing with polymeric material, and was gradually increasing by 0.05mm to 0.8mm in diameter. Additionally, a line pattern was printed to check resolution and bonding between the layers, varying the diameter of output parameter in the software to compensate for changes in the nozzle.

Table 3. Nozzle Tests

Nozzle Ø (mm)	Continuous Flow	Time without clogs (s)	Observations
0.40	No	3	Very Thin, some blank spaces
0.45	No	4	
0.50	No	5	Some clogs, separated lines
0.55	Yes	6	
0.60	Yes	10	Well-formed lines and separations.
0.65	Yes	10	
0.70	Yes	10	Constant flow, overlapping lines.
0.75	Yes	10	Overlapping lines, Material flow with motor off.
0.80	Yes	10	

Table 3 shows a summary of tests performed to determine the best nozzle diameter depending of the composite behavior. For diameters smaller than 0.5mm, the nozzle tends to become clogged generating an irregular flow, and some spaces remain unprinted. For diameters between 0.5mm and 0.7mm, and the flow is more constant with almost no obstructions and the printed lines are well defined, but for diameters larger than 0.7mm, the flow is abundant and lines overlap each other, and it was observed that the material was flowing out even if the motor was turned off, only due to gravity, which is not suitable for the printing process where it is required to control the times when printing is required. Because of these considerations, the diameter of the nozzle for the printer extruder head was 0.6 mm, 50% larger that of the nozzles used to print polymer material without fibers. Figure shows the filament before and after extrusion by the printer.

Figure 8. 1.75 mm filament (top) and extruded filament (bottom)

Figure 9 shows a printed sample using the filament, at 1x, 10x and 20x. The filament layers and line overlapping can be observed. The presence of natural fibers can be clearly observed, and it is demonstrated that the filament can be used to obtain a 3d part since the material layers are joined and the material is deposited in the necessary points in order to obtain the modeled part. Additionally it can be seen that the size of the fibers in the material is not constant, explaining why the gear drive and tensioning system must be used.

Figure 9. 3d printed sample. (Top). 10x close up (Bottom Left) and 20X (Lower Right)

The material chosen for the thermoplastic matrix is very flexible, so the parts that have been printed are 2D with volume, but further investigations are in process to obtain a functional filament using PLA and ABS. In order to obtain this, other additives are needed in the extrusion process as explained above, and additionally a double screw extruder with volumetric dosing is suggested. However, these developments are very promising, because it verifies that the head is able to print composite materials manufactured locally, providing autonomy and opening a research line to obtain new products or prototypes of composite materials using additive manufacturing.

CONCLUSIONS

The presented work shows the design and development process followed in order to obtain a natural fiber reinforced composite filament suitable for using in 3d printing by FDM. The reverse engineering process was a very useful tool in order to understand the process, functions, and parts that make up a 3d printer and how several recommendations must be followed in order to print with natural fiber reinforced composites. The design of experiments with the fiber volume percentage and the different types of polymer matrices was useful to identify additional elements required for producing local composite filament for 3d printing. Despite the composite is only acting as a filler rather than a reinforcement, chemical treatments in the fiber and the inclusion of other additives can help improve the mechanical properties, but this partial results demonstrate the viability of 3d printing with locally produced natural fiber reinforced composites.

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