Application of Additive Manufacturing in the Manufacture of Ophthalmic Frames

Aplicación de la Fabricación Aditiva en la Manufactura de Monturas Oftálmicas

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Artículo de investigación científica y tecnológica

***Abstract*—This study examines the properties of recycled polyethylene terephthalate (PET) filament applied to the manufacture of ophthalmic frames by additive manufacturing. Applied research from a quantitative approach was used under the multi-criteria decision-elimination and choice (AHP) method, to determine the best material. The results allowed obtaining a customized frame in recycled polyethylene terephthalate (PET) based on anthropometric measurements. The study concludes that 3D printing applied in manufacturing processes is an excellent option that responds to the demand for the new and sustainable alternative materials for 3D printing filaments, facilitating product customization. In addition, the tests carried out on the frames show that it meets the requirements for dimensional stability, sweat resistance, resistance to ignition, and good properties considered in the data obtained in the flexion, tension and impact tests.**

***Index Terms*— Additive manufacturing, 3D printing filament, Ophthalmic frames.**

***Resumen*—Este estudio examina las propiedades del filamento de polietileno tereftalato de etileno reciclado (PET) aplicado a la manufactura de monturas oftálmicas mediante fabricación aditiva. Se utilizó la investigación aplicada con enfoque cuantitativo bajo el método de decisión multicriterio de eliminación y elección (AHP), para determinar el mejor material. Los resultados permitieron obtener una montura personalizada en polietileno tereftalato de etileno reciclado (PET) basada en las medidas antropométricas. El estudio permite concluir que la impresión 3D aplicado en los procesos de manufactura es una excelente opción que responde a la demanda de la nueva y sostenible alternativa de materiales para los filamentos de impresión 3D, facilitando la personalización de productos. Además, las pruebas realizadas a las monturas dan cuenta que cumple con los requisitos de estabilidad dimensional, resistencia al sudor, resistencia a la ignición, y buenas propiedades consideradas en los datos obtenidos en los ensayos de flexión, tensión e impacto.**

***Palabras claves*— Fabricación aditiva, Filamento de impresión 3D, Monturas oftálmicas.**

I. Introduction

Plastics are materials made up of organic, synthetic, and semi-synthetic compounds used in various applications due to their low cost and properties based on molding, that is, malleability or plasticity. Due to its relatively light weight, accompanied by flexible and hygienic properties, it is used in the packaging industry, taking the form of trays, containers, bottles, bags, and others. In addition to the packaging industry, it is used for the transport of fluids in liquid, gaseous and colloid state. It is also applied in the automotive industry for the acquisition of forms that are part of systems, thanks to the high resistance ratio it presents [1]. Likewise, the generation of products manufactured from plastic that have been accompanied by a touch of personalization has gained interest. This has been achieved, thanks to the development promoted by the concept of industry 4.0, which is understood as a new industrial stage of technological advances in products, processes and smarter services where an integration between manufacturing systems and information and communication technologies takes place (ICT) [2]. For this case, one of the tools used in these processes corresponds to 3D printing or fused deposition manufacturing, where a set of additional manufacturing features allows a three-dimensional object in specific software to be created by superimposing successive layers of material [3].

Additive manufacturing (AM) or addition manufacturing is a new production concept, whereby the plastic or metal material is superimposed layer by layer in a controlled manner in sections where it becomes necessary [4][5]. Compared to other traditional manufacturing techniques, it reduces intermediate processes, such as the production of tools, allowing parts to be obtained up to 90% faster, reducing waste and, most importantly, saving energy.

At first glance, 3D printing and additive manufacturing terms are often related as synonyms, however they are not the same. Additive manufacturing refers to the manufacturing techniques by adding different materials used to produce complex and durable new products. Whereas, 3D printing, as rapid prototyping, refers to the manufacture of models and parts with limitations that are usually associated whit the use of a specific type of additive technology [6].

According to the needs of each sector, the additive manufacturing process can be produced or developed from different technologies, where the choice between them will depend on various factors such as the functionality that the final part produced will have, or if you want to manufacture including polymers or metal alloys.

The main technologies of additive manufacturing are

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powder bed melting, fused deposition modeling, Jetting or resin printing, and 3D printing [4][7]. The latter is a process by which physical objects are made by placing a material determined by layers based on a previously created digital model. All the processes involved in 3D printing require that the software, hardware, and materials work together. This technology is applied with infinite possibilities and in various sectors of the industry, where designs and prototypes brought to reality can provide an economic solution for all those who have a need [8].

Studies that relate the additive manufacturing process focusing on the production of ophthalmic frames are few, however, they have been gaining interest in the product customization market. In [9] A study was carried out on the development of phosphate glasses with preserved physical properties, modeled by molten deposition whose applications may been aimed at optical components. In the field of optical lens manufacturing, the results obtained in [10], that minimized the problems of staggered lens surfaces and, in [11] the results of which minimize the surface roughness of the printed structures, which negatively affects the propagation of light in 3D printed optical components. Other studies have developed the technology to enable 3D printing of transparent glass objects, an option that was previously beyond the reach of standard 3D printers. [12][13]. Finally, in [14] an investigation is carried out that validates the use of polymeric materials such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), and its compatibility with the human face, implementing it in users who need optical corrections, and in [15] a study aimed at personalizing glasses for children with craniofacial abnormalities.

From this point of view, the opportunity to take advantage of the production tools of Industry 4.0 is identified; where additive manufacturing waste materials can be incorporated and made useful, therefore, this research aims to produce ophthalmic frames by additive manufacturing taking advantage of recycled polyethylene terephthalate (PET).

II. Materials and methods

For prototype printing, a Prusa I3 reference hybrid printer is implemented as shown in Fig. 1, with a printing bed of 20cm X 20cm X 20cm with a maximum temperature range of 70° C, extruder with a maximum temperature of 250° C and a 0.4mm extrusion nozzle.

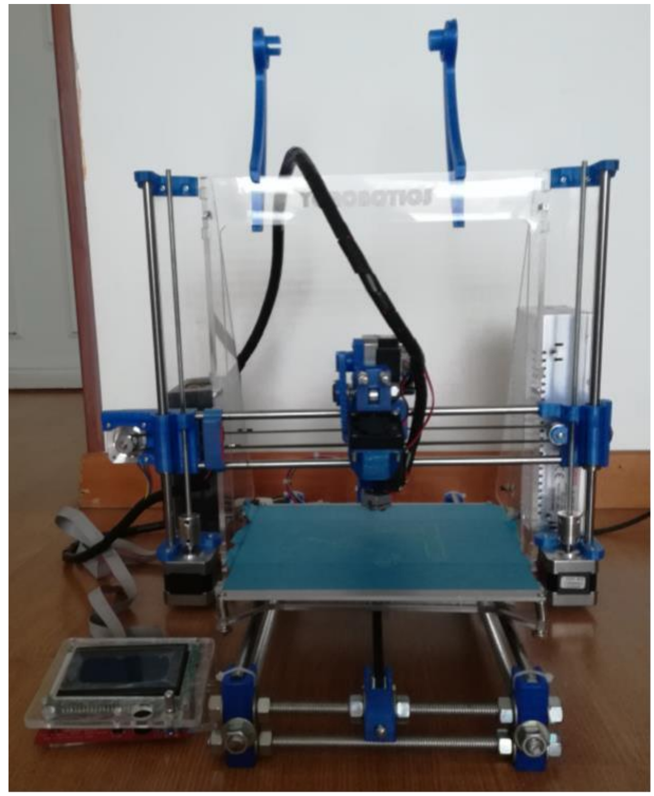

Fig. 1. 3D Printer Prusa i3.

The frame design process was carried out in SolidWorks software and the model was subsequently exported to the Open Source Cura software, as can be seen in Fig. 2a and Fig. 2b. In the mentioned machine, six frames were manufactured with the dimensions established by the NTC 5607 standard. Under this perspective, the standard suggests applying the dimensional stability tests at high temperatures, the sweat resistance test, and the ignition resistance test. The above was carried out in the laboratory of the ECCI University.

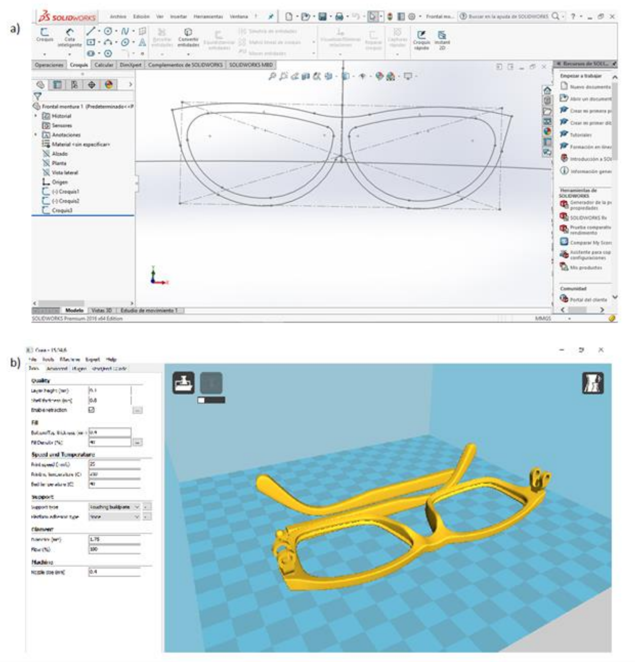

Fig. 2. Design process: a) Model in SolidWorks, b) Model in Cura

For the development of the flexural tests, the reference was the ASTM D790 standard, for the stress test it was the ASTM D638 standard and, the impact resistance test following the ASTM D256-10 standard. The equipment used for this test is owned by the materials laboratory of the National University, under the brand SHIMADZU, MODEL AGIS-5 KN AND SERIAL No.130104403667.

To determine the material and the suitable manufacturing method, the hierarchical analysis method (AHP) was implemented, which is a tool that facilitates making decisions to achieve an adequate result; Its implementation refers to solving problems that are highly complex and in which multiple criteria must be taken into account. This method requires that the person making the decision establishes subjective evaluations regarding the relevance of the defined criteria and then the preference based on each of the decision options must be clarified; the result of this process is a prioritized hierarchy that shows preference from the previously defined decision alternatives [16].

III. Results

A. *Selection of plastic material and the additive manufacturing method for the elaboration of ophthalmic frames*

Once the possible materials with which the frames can be made with 3D printing have been identified, as can be seen in Table I, the development of the AHP method yielded a score of 22 for PET, 17 for POLYSTYRENE (HIPS), 17 for acrylonitrile butadiene styrene (ABS) and 20 for polylactic acid (PLA).

TABLE I
MATERIALS SELECTION CRITERIA

Criteria	0	1	2	3
warping	not apply	Unstable	Stable	Very stable
Synthetic or natural	n	N.A.	Synthetic	Natural
Print resolution	not apply	Low	Mid	High
Extruder temperature	not apply	More than 240 C*	between 240 and 220	Les than 220
Bed temperature	not apply	More than 50 C*	between 40 and 50	Les than 40
Impact resistance	not apply	Low	Mid	High
Flexibility	not apply	Low	Mid	High
Filament diameters	not apply	3,85 mm		1,75 mm

Source: Exconde, Co, Manapat and Magdaluyo, 2019 [1].

It is important to note that the temperature range used in 3D printing for this type of plastic materials is from 215 to 250 ºC. These parameters vary according to the specifications of the printer to be used. For this study, the optimum printing temperature is 230 ºC and requires the hot bed to be at approximately 65ºC to ensure adhesion of the material to the plate and guarantee that the printing layers are the best.

B. *Tests for dimensional stability at high temperatures, sweat resistance and ignition resistance*

The normative reference contemplated in NTC 5607 in numeral 4.6 establishes a tolerance of +/- 5mm for the dimensional stability test at high temperatures (see Fig. 3a). The results obtained allowed to identify a variation of the frontal (0.097 mm), height (0.047 mm) and arms (-0.409 mm) measurements. The foregoing verifies that the selected material does not show a greater variation, these being within the specified tolerance range. Regarding the test for sweat resistance (see Fig. 3b), the standard indicates in numeral 4.7 that there should not be a change of color in the frame excluding the hinges and screws after 8 h. In this regard, it can be determined that the sample exposed to the test does not present significant variation in coloration on its surfaces (front and arms) and especially on those that will have contact with the skin of the end user. However, it is evident that in some sectors of the sample there is separation of some of its printing layers. Finally, the results for the ignition resistance test (see Fig. 3c), the standard in numeral 4.9 indicates that the material must not continue combustion once the test bar is removed. When executing the test, it is possible to identify that the test piece does not show ignition after removing the metal bar. In addition to this, a deformation can be observed in the material due to the high temperature of the bar.

Fig. 3. Design test: a) Stability, b) Sweat resistance, c) Ignition resistance

C. Tensile strength test (tensile strength and elongation)

This test was developed taking into account the ASTM D638 standard with type I specimen (σ <5000N). The results presented in the six test tubes SD = 110,654 with a maximum value of 1,522.97 N and a minimum of 1,221.56 N. Table II shows the results as well as the reference values of the commercial materials with which ophthalmic frames are manufactured.

TABLE II
REFERENCE VALUES OF TENSILE STRENGTH IN MATERIALS FOR OPHTHALMIC FRAMES

	Cellulose acetate	Cellulose propionate	Epoxy resin	Polyamide	Carbon fiber	Pet recovered
Material	CA	CP	EP	PA	CF	PET
Tensile strength (N/mm2)	30-50	30-50	75	75	1800	15,1

When executing the tensile strength test, it is evident that values lower than the commercial ones are obtained, which responds to the fact that polymers are molecules formed by the repeated unions of one or more molecules linked by bonds. Within these bonds, the polarity and volume of these atoms will especially affect the cohesion forces between chains, which in turn, will establish the flexibility of the material, its melting temperature, and its crystallization capacity. The higher they are the cohesion forces between chains, the polymer will obtain more rigidity and melting temperature, applying to crystalline polymers such as PET.

In turn, it is necessary to highlight that in the polymerization processes the monomers are joined in the same way, this in the case of PET. Within this structure, branches are formed providing free volume and separation between chains, related to the density of the polymer and its crystallization, forming chemically and geometrically regular molecules in its structure [17]. On the other hand, in the molten or liquid state, the molecules of this polymer are shrunk and entangled if there is no external force that forces them to be oriented in one direction.

From the above, it is established that it is necessary to make a structural change in the mesh of the piece at the time of printing it, since the triangular mesh configuration as in the printed and tested prototypes, the distribution of the applied stress is not proportional, which mainly influences the resistance capacity and the values obtained in the test carried out.

D. Flexural strength test

This test was developed considering the ASTM D790 standard with a rectangular geometry of 100 mm long, 15 mm wide and 3.75 mm (σ <5000N). The results in the six specimens showed an SD = 5.940 with a maximum value of 132.594 N and a minimum of 114.406 N. Table III indicates the results obtained, as well as the reference values of the commercial materials with which the ophthalmic frames are manufactured.

TABLE III
REFERENCE VALUES OF FLEXURAL STRENGTH IN MATERIALS FOR OPHTHALMIC FRAMES

	Cellulose acetate	Cellulose propionate	Epoxy resin	Polyamide	Carbon fiber	Pet recovered
Material	CA	CP	EP	PA	CF	PET
Tensile strength (N/mm2)	24 - 71	40-60	110	70	70	44,1

The results allowed us to identify that PET presents a better behavior compared to the most used and resistant commercial material known as acetate. This phenomenon can be explained by the fact that the level of crystallinity and the orientation of the fibers is not the same in extruded materials as in injection molded materials, which results in important differences in values.

E. Flexural strength test Impact resistance test

This test was developed taking into account the ASTM D256-10 standard with a specimen with a maximum capacity of 22 Jules. The results presented in the six specimens SD = 0.001 with a maximum value of 0.018 and a minimum of 0.007 fracture toughness. Table IV shows the results, as well as the reference values of the commercial materials with which the ophthalmic frames are manufactured.

TABLE IV
REFERENCE VALUES OF IMPACT RESISTANCE IN MATERIALS FOR OPHTHALMIC FRAMES

	Cellulose acetate	Cellulose propionate	Epoxy resin	Polyamide	Carbon fiber	Pet recovered
Material	CA	CP	EP	PA	CF	PET
Tensile strength (N/mm2)	50-80	50-80	130	130	70	15-35

The results obtained in the impact resistance test indicate that the selected material has lower values than the commercial reference materials. It should be noted that these results suffer variations due to the influence of variables such as the temperature at which the polymer is at the time of execution of the test, directly affecting the toughness of the polymer subjected and the speed of the applied load. The polymer will have a greater probability of failing to become a brittle material at a higher speed, due to the lack of time for the intermolecular force to be effective. If the test is carried out at low temperatures and high speeds, the material will obtain lowest impact resistance possible [18][19].

In addition to the above, it is necessary to consider the ductility and brittleness of the material. The first allows a plastic deformation before breaking and the brittleness corresponds to a microscopically smooth or grooved break when exposed to low force. The latter is closely related to the speed with which crack growth spreads throughout its structure [20].

Last and not least, within the process of molding parts with the help of raw material based on recovered materials, there are factors that directly affect their resistance. Due to the reprocessing of the material the molecular chains are modified, generating residual stresses [21][22], defective welding lines (adhesion between layers) and crystallization of these in some sections. In turn, the specimens made and as mentioned above, has a triangular mesh within its internal structure that leaves internal voids causing volume deficiency that helps to the absorption and dissipates the impact to which it is subjected [19].

IV. CONCLUSIONS

The characterization of the material using the AHP method, allowed defining that PET has the mechanical, thermostability and low-cost properties necessary to be implemented in 3D printing processes.

These processes can be carried out using devices operated with free software, which favor flexible manufacturing and maintain surface finish conditions.

Finally, laboratory tests based on the national and international regulatory framework show that flexural strength is higher compared to commercial materials, however, the results of the impact resistance test are below the same materials, finding that during the process of molding parts with the help of raw material based on recovered material, the molecular chains are modified, generating residual stresses and minimizing the values for this test.

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