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EDUCATION & TRAINING

Novel Technique Based on Fused Filament Fabrication (FFF) and Robocasting to Create Composite Medical Parts

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Abstract

The purpose for this study is to obtain a new composite manufacturing system based on Additive Manufacturing techniques that allows the creation of parts for the medical industry. These pieces will be resistant, lightweight and may have geometries more complex than those created with traditional systems of composite material. The new system is based on the union of two heads on a 3D Rep-Rap printer. One of the heads is an extruder head of thermoplastic Fused Filament Fabrication (FFF) and the other is a dosing head, based on the Robocasting technique, designed to be assembled on the 3D printer. Thermoplastics material and epoxy resin will be used. The alternate printing of both materials generates a piece of composite material. This new technique will allow to increase the structural properties of the piece in the XY plane. The new additive manufacturing system allows to obtain mechanical improvements both in the modulus of elasticity and in the tensile strength. Increase the modulus of elasticity of a value between 50 and 80% depending on the thermoplastic filament used. In the same way the tensile strength has increased between 50 and 60%. The improvement in the strength / weight ratio allows to this new additive manufacturing system to create medical pieces in which the lightness and resistance are its main characteristic, such as orthopedic prostheses.The results show that the use of FFF together with Robocasting, as a manufacturing process for end-use parts, generates an additional advantage that had not been considered until now. The combination of a thermoplastic and an epoxy resin opens a new path in the additive manufacturing since it allows creating pieces with new qualities without being conditioned by the design.

Keywords FFF · Robocasting · Composite · Medical parts

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Introduction

The phenomenon called Additive Manufacturing has received a great boost from many industries, both from the point of view of research and production. According to the report of Wohlers Associates Inc. of 2016, the CAGR (Compound Annual Growth Rate) of products and services of AM worldwide grew by 25.9% reaching 5165 billion $. This value includes industrial equipment and desktop machines but does not account for the research and development initiatives of the manufacturers and their suppliers, therefore the income of everything surrounding the AM is even greater than the previous economic value [1].

As seen in the economic data, additive manufacturing is a technology with great potential that is enabling many companies to invest in R + D + i. A clear example of this implementation is happening in the medical industry, which has been working with this technology for 15 years and whose prognosis is a 23% growth between 2015 and 2025 [2].

Table 1 Type of test specimens

Indirect	Manufacture of molds or pieces bases	Obtain a mold to create pieces of composite material [32]		
		Create a piece of end use with complex geometries that will later be reinforced by a curb, manually or automatically, with CFRP to improve the mechanical properties of the piece made of thermoplastic [33, 34].		
		Fabricate reinforced parts by including sheets of CFRP in the FFF process increase the mechanical properties of the piece made of thermoplastic [35].		
		The use of soluble cores offers the possibility of making parts that will be used to manufacture hollow CFRP parts with complex geometries [36].		
	Tooling manufacture	The manufacture of tools through FFF allows to accelerate the final production process due to the design improvements [37].		
Direct	Filament with fibre or particles	*Reinforcement*	*Size*	*Material*
		Fibre	Nanotube	Carbon [38, 39]
			Matrix & short	Carbon [40, 41]
			Short	Glass [42, 43]
			Long	Carbon, glass [44]
			Continue	Carbon [45, 46]
		Particles	Nano	Carbon (graphene) [47]
				Montmorillonite [48]
			Metal	ABS –Iron [49, 50]
				Nylon- Iron [51, 52]
				ABS- Copper [50, 53]

In recent years the optimization of production processes [3] together with the study of new materials [4, 5] has made it possible to improve the performances [6] and design of medical products [7]. The medical industry has always used the most modern manufacturing systems to improve quality and safety of the new products. Additive manufacturing is used in many areas of medicine. The creation of dental pieces using the SLM technique (Selective Laser Melting) [8, 9] the manufacture of orthopaedic prostheses or the design and fabrication of reconstructive mandibular models using the FDM (Fused Deposition Modelling)) [10, 11] and the design and creation of tissues and organs with organic ink [12–14] are some examples of the benefits of additive manufacturing in medicine. [15]

At the same time, there is a growth in the use of advanced composite materials in medicine such as CFRP (Carbon Fiber Reinforced Plastics), in which the correct combination between carbon fibre and an organic matrix (epoxy) generates a material with better properties than the parts that compose it separately [16]. This material is used in modern orthopaedic medicine and prosthetic devices [17] as well as in cases of cranioplasty [18]. For this reasons the aim of this study is to present a new Composite material created by the combination of additive manufacturing techniques FFF and Robocasting. This combination allows obtaining a new manufacturing system based on the union of two heads on a 3D Rep-Rap printer. One of the heads is an extruder head of thermoplastic FFF and the other is a dosing head, based on the Robocasting technique, designed to be assembled on the 3D printer. In order to evaluate the mechanical characteristics of the new composite material, various tensile tests have been carried out on different specimens generated with the proposed technique. The study develops starting from the manufacture of the new 3D printing system, with the two print heads mounted on a commercial printer. The second step is to present the production technique of the specimens for the tensile tests produced starting from the proposed combined AM technique. And finally, the results of the tensile tests carried out according to international standards with respect to the elasticity modulus and tensile strength will be presented.

Fused filament technologies (FDM /FFF)

The terminology FFF appeared together with the Rep-Rap (Replication of Rapid Prototyping) movement [19] to give a different name to the FDM (Fused deposition Modelling) technique of Stratasys Inc. whose patent had been liberalized in 2009. The printing process consist of in depositing layers of thermoplastic until creating the designed piece. The machine has a heated extruder that heats the material until its vitreous transition so that it can flow and deposits it creating a layer that matches one of the sections of the design of the piece in 2D. Each time a layer is created, there is an increase in height of the extruder that allows generating the third dimension of the piece by overlapping the layers. The thickness of the built layer and the vertical dimensional accuracy is related, among

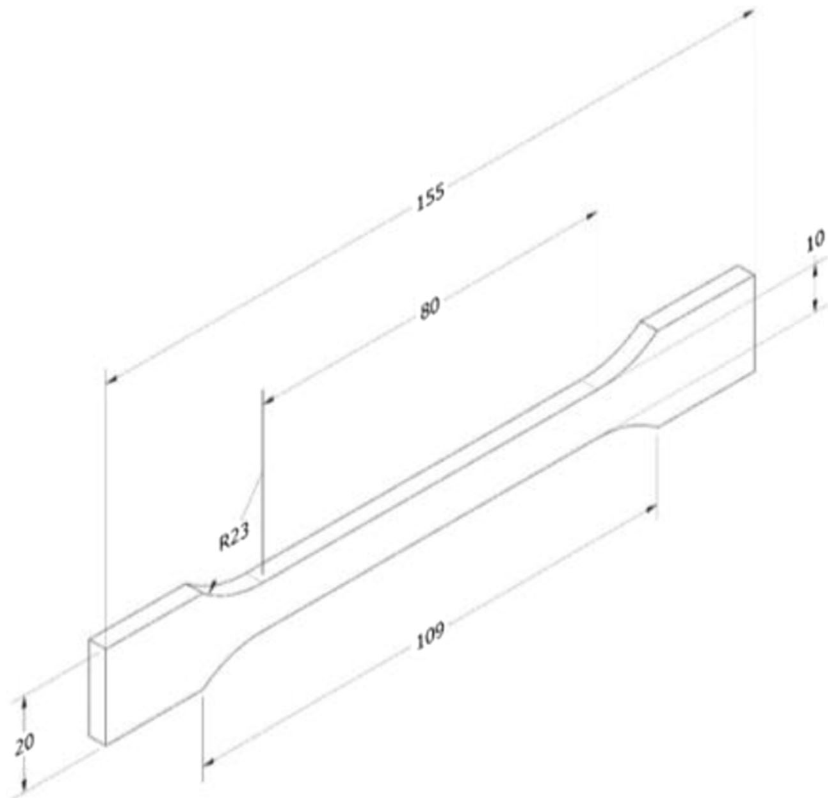


Fig. 1 Measures of the test specimens

other aspects, to the diameter of the extruder, whose range is from 0.1 to 0.8 mm [20, 21].

Robocasting

Robocasting is an AM technique that consists in creating pieces through the deposition of ceramic paste cords. The principle of operation is identical to that used in the FFF technique with the fundamental difference that the head that generates the piece is not a heatable extruder head but is a dosing extruder head. The dosage is made by an injector because the material with which the piece will be made is in a pasty state or gel. The total curing of the piece occurs when the ceramic paste has hardened, this process can last for hours [22]. Within the field of AM dosing, new utilities have been incorporated, ranging from the bio printing of gels to make human tissues [23] to the creation of food with pasta [24].

Composite material in FFF & robocasting

AM has quite similarity with the manufacture of composite materials. In both cases the process consists of depositing successively layers to create the final piece [25]. The fundamental difference between both technologies is in the process of adhesion of the layers. In the manufacture of composite materials, fibre layers pre-impregnated with resin are first deposited on a mold to be subjected to pressure and temperature, thus obtaining the desired part, which requires a post-process to be considered as a final piece [26].

Very similar to the technique described in this article (FFF) there are the LOM technique (Laminated Object Manufacturing) the piece is obtained by the adhesion of fine laminated material [27, 28] and SLA (Stereolithography) in which the composite material is obtained by incorporating particles inside the main material (photo curable resin) [29,

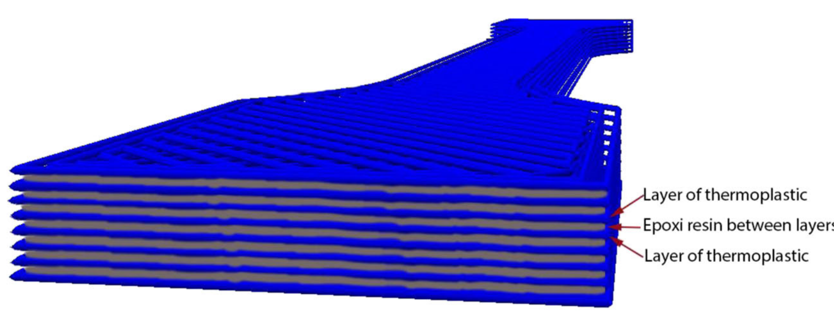


Fig. 2 Scheme test specimen design

Fig. 3 Image of the adhesive extruder (design and manufacture)

30]. In addition, there is the possibility of mixing the Robocasting technique with other AM techniques [31].

Manufacture of composite material using FFF

As discussed above, this study presents the manufacture of advanced composite material. The article focuses on processes that achieve CFRP properties. In fact, the goal is to manufacture parts that improve the ratio between mechanical properties and weight. It is important to note that this increase in resistance occurs only in the XY direction. The use of the FFF technique in the manufacture of composite materials can be seen in Table 1.

Material and methods

In the creation of the composite material specimens, 2 types of materials, thermoplastics and epoxy adhesive have been used. The thermoplastics have been supplied in the form of yarn with an outer diameter comprised between 2.85 and 3 mm in diameter. The study contemplates the following thermoplastics: PLA (polylactic acid) and PLA reinforced by cuts of carbon fibers (15%) manufactured by Proto-pasta. Regarding epoxy adhesives, it has been used in two-component format and in a 50 ml cartridge. These cartridges are on the market with standardized dimensions to be used in dosing guns. The chosen epoxy adhesive has been Loctite EA 9461 A & B mainly for its suitability in the union of thermoplastics, for its curing at room temperature and for having a curing time of 240 min. This last characteristic allows the manipulation during the printing process and prevents it from solidifying in the nozzle in the process of waiting between layers.

Design

The test pieces have been designed according to UNE 116005_2012 “Manufacture by addition of layers in plastic materials”. The design has been developed in two distinct parts. First of all, the specimen was designed in 2D (Fig. 1) and later in 3D to obtain the. Stl files and then the gcode. Secondly, based on the previous design, two files have been obtained that have allowed us to obtain the bimaterial specimen in amf format. The result of this design has allowed

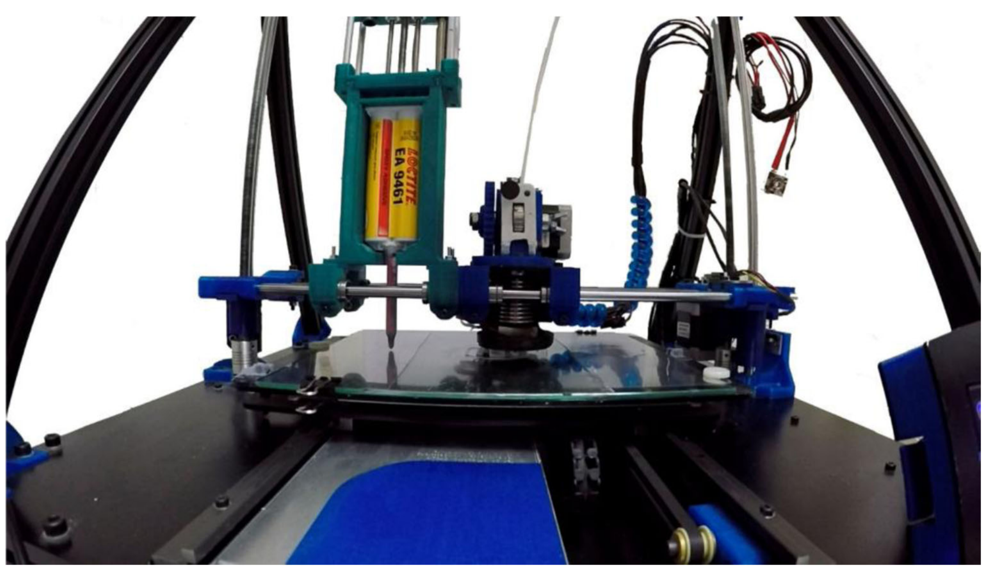


Fig. 4 Image of the design of the BCN 3D + printer modified for the creation of pieces of composite material

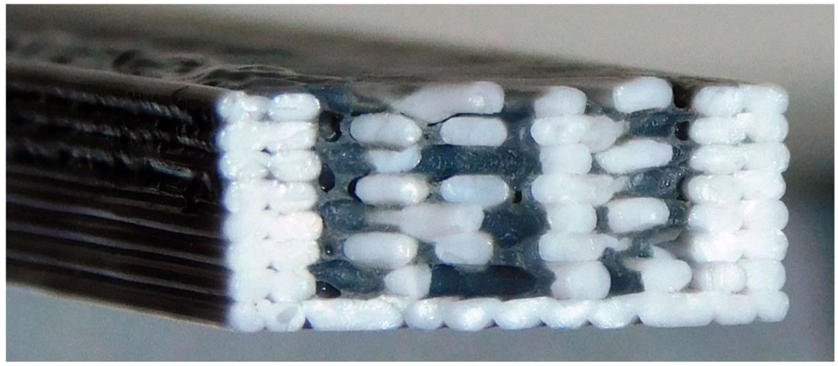


Fig. 5 Image of a rupture section of a test specimen

obtaining specimens with interlayered layers of thermoplastic and epoxy (Figs. 1 and 2).

Manufacture of test specimen method

For the manufacture of the specimens, an adhesive extruder head has been designed that has been manufactured using the FFF technique (Fig. 3). This new extruder has been implemented in an AM RepRap BCN 3D + machine, from BCN3D Technologies next to the thermoplastic filament extruder (Fig. 4). The joint printing of both materials, in alternating layers, will generate a composite material that has allowed increasing the structural properties of the piece in the XY plane.

Printing characteristics

The creation of the composite material is done by alternate deposition of the two materials. The first layer deposited is the one of thermoplastic with a filling of 100% to create the base of the piece that is being printed. Next, the epoxy resin layer is deposited with a perimeter reduction to allow the joining between the thermoplastic layers to be ensured by depositing the next thermoplastic layer. The diameter of the nozzle of the epoxy resin cartridge is 2 mm, therefore, a diameter of 0.8 mm has been chosen for the thermoplastic extruder looking for maximum equality in the outlet diameter of both materials. The 3D printer rises 0.5 mm each time it deposits a layer of thermoplastic. In each epoxy resin deposition process there is no variation in height with respect to the printing of the thermoplastic front layer. The difference in height between the two heads of the 3D printer is 0.1 mm in favour of the epoxy dispenser and has been achieved thanks to the design of the hardware. This height is necessary to guarantee the correct deposition of the resin on the lower layer because it avoids the creation of drops due to the surface tension and therefore we avoid irregular dosages.

Fig. 6 Image of impression

The printing process is linear with a material filling in the initial and final 100% layer. In the rest of the layers a 75% filling is produced in order to intermix both materials and create a composite (Fig. 5). The angle in the deposition process is 45° alternating the orientation between each thermoplastic layer (Fig. 6).

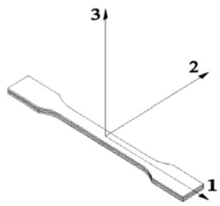
Tests

The test pieces and tests have been carried out according to the requirements contemplated in the UNE 116005–2012 Standard "Manufacture by addition of layers in plastic materials". For this reason, 6 units of each test piece will be produced, generating a total of 36 specimens that will serve to cover the 6 cases that are to be studied (Table 2). With these tests it is intended to observe the temperature influence of epoxy curing on the mechanical characteristics of the specimens. The maximum resistance of the epoxy is obtained from 60 °C. Therefore, due to the glass transition temperature of the PLA the curing temperature for the heat test was carried out at 60 °C to avoid deformations of the PLA.

Results

The tests were carried out with a brand traction test machine: Ibertest model: Eurotest-100. The specimens with epoxy have seen their weight increase by 1 g with respect to the samples without epoxy whose weight is 10 g. Figure 6 show and

Table 2 Type of test specimens.

Impression orientation	Thermoplastic	Epoxy	Curing Temp.	Test	Nomenclature
Horizontal 	PLA	Without	T_{amb} (23ºC)	Tensile	PLA
		Loctite EA 9461 A&B	T_{amb} (23ºC)	Tensile	EPLA
		Loctite EA 9461 A&B	60º C	Tensile	EPLAH
	PLA + Carbon fibre	Sin	T_{amb} (23ºC)	Tensile	PLAC
		Loctite EA 9461 A&B	T_{amb} (23ºC)	Tensile	EPLAC
		Loctite EA 9461 A&B	60º C	Tensile	EPLACH

example of impression. Figures 7 and 8 show the modulus of elasticity and the tensile strength, respectively.

Discussion

Figure 7 shows the modulus of elasticity for the different test pieces tested. It is noted how the modulus of elasticity increases as the epoxy adhesive and the carbon fibre particles are included in the thermoplastic. This fact is coherent taking into account that the module is closely related to the capacity of elastic deformation of the material. In this case, the PLA with carbon fibre particles increases its rigidity by 67% with respect to the PLA. This is due to the internal cohesion between the fibres and the thermoplastic. The incorporation of epoxy has increased the rigidity in both PLA and PLAC. For the PLAC major the increase has been greater due to the incorporation of

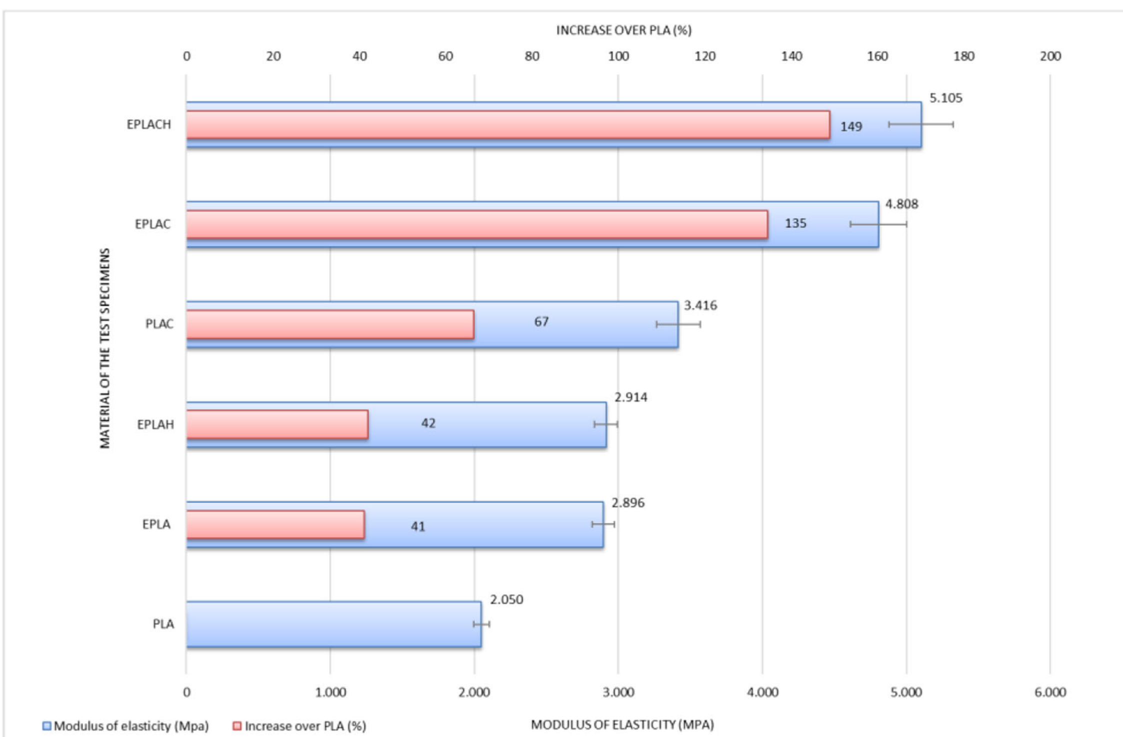


Fig. 7 Modulus of elasticity

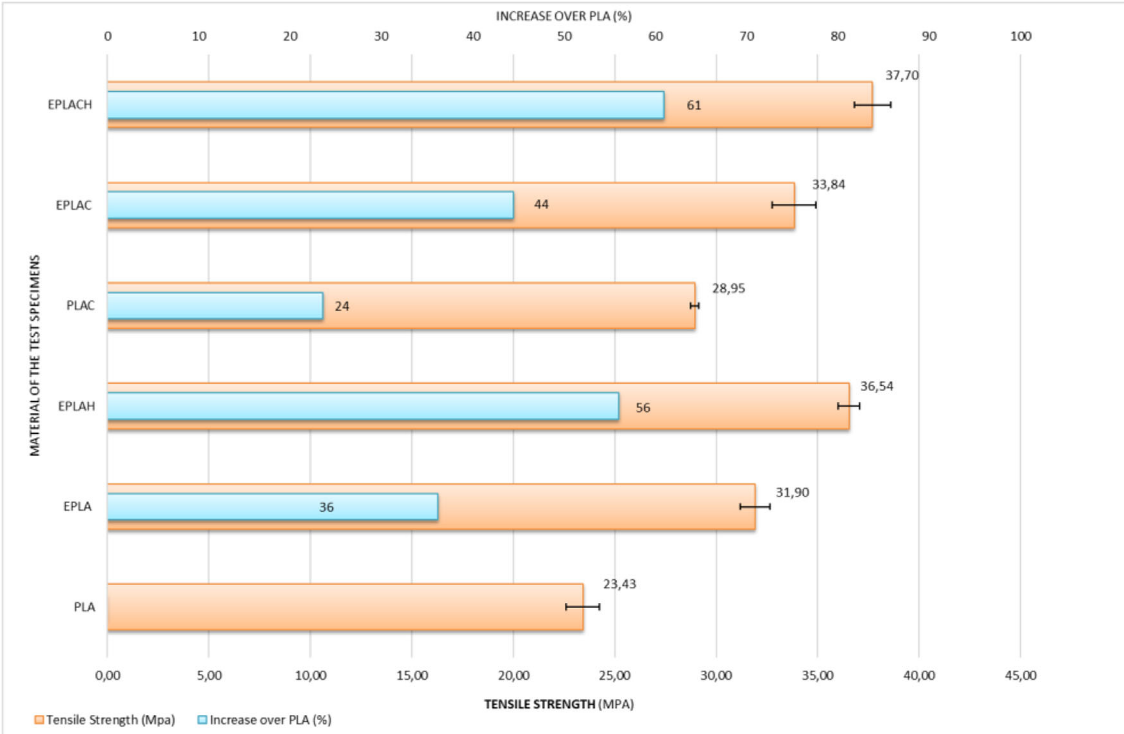


Fig. 8 Tensile strength

fibers that gives greater surface roughness, a situation that allows the epoxy to adhere better to the thermoplastic filament. The highest stiffness is obtained after the curing process in the oven. This has allowed to reach an increase of 149% of the EPLACH test tube compared to the PLA. Looking at Fig. 8 it can be seen how the tensile strength have a positive tendency both in PLA and in PLAC. On the one hand it is observed that the incorporation of the epoxy adhesive increases the tensile strength of the test pieces in the case of the PLA by 36% and in the case of the PLAC by 44% with respect to the PLA and 20% with respect to the PLAC without epoxy. It can also be seen how the curing of the test pieces in the oven at 60 °C. favours the increase of the tensile strength due to the increase in the mechanical properties of the epoxy.

Conclusions

The aim of this study is to present a new Composite material created by the combination of additive manufacturing techniques FFF and Robocasting. This combination allows obtaining a new manufacturing system to create pieces of composite material usable in the medical industry. In this study, the FFF and Robocasting technique has been used to intermix the epoxy resin between the thermoplastic structure of the piece allowing to increase the mechanical properties without the weight increasing considerably. The new system is based on the union of two heads on a 3D Rep-Rap printer. One of the heads is an extruder head of thermoplastic FFF and the other is a dosing head, based on the Robocasting technique, designed to be assembled on the 3D printer. In order to evaluate the mechanical characteristics of the new composite material, various tensile tests have been carried out on different specimens generated with the proposed technique. The specimens were fabricated using PLA thermoplastic material with and without carbon fibre reinforcement and with different curing temperatures for the epoxy resin. The results show that the weight of the specimens increases by 10% due to the inclusion of the epoxy resin but the increase in modulus of elasticity can reach 149% and the tensile strength to 61%. In addition, the new technique allows to obtain complex designs without reducing the mechanical properties of the pieces, therefore, with this new manufacturing technique a new space opens up to creativity within the field of composite materials.

Compliance with ethical standards

Conflict of interest Alberto Sánchez Ramírez declares that he has no conflict of interest. Roberto D'Amato declares that he has no conflict of interest. Fernando Blaya Haro declares that he has no conflict of interest. Manuel Islan Marcos declares that he has no conflict of interest. Juan A. Juanes declares that he has no conflict of interest.

Ethical approval This article does not contain any studies with human participants performed by any of the authors. This article does not contain any studies with animals performed by any of the authors.

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