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# Design of experiments (DOE) of parts manufactured in 3D printers using composed filaments of PLA and Aluminum

# Diseño de experimentos (DOE) de piezas fabricadas en impresoras 3D utilizando filamentos compuestos de PLA y Aluminio

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**Abstract**

The Department of Mechanical Metal (Mechatronic Engineering) of the Technological Institute of Nogales was one of the first national degrees to offer in its study plans the specialty of plastic injection molding (IMCE-MIP-2017-01), with the eager to continue innovating and evolving in this area, we present the following research work, with which we experimented and generated knowledge to determine the mechanical properties of parts manufactured in 3D printers, with polymer composite materials (PLA) and metallic powders ( Aluminum). In the first place, the filament formed by a matrix of PLA and an ALUMINUM reinforcement was created, which was extruded in a molding machine manufactured inside in the molding laboratory of this Institute, taking as consideration that the reinforcing material in this case aluminum the following percentages will be 0% and 20%. Placing these filaments in a suitable printer for the manufacture of 3D parts with composite materials to which an analysis of experiments was performed to determine what percentage of composite material has better mechanical properties

**PLA Filament, Composite Material, Design of Experiments (DOE)**

**Resumen**

El departamento de Metal Mecánica (Ingeniería Mecatrónica) del Instituto Tecnológico de Nogales fue de las primeras licenciaturas a nivel nacional en ofrecer dentro de sus planes de estudio la especialidad de moldeo por inyección de plásticos (IMCE-MIP-2017-01), con el afán de continuar innovando y evolucionando en esta área, se presenta el siguiente trabajo de investigación, con el cual se experimentó y generó conocimiento para determinar las propiedades mecánicas de piezas fabricadas en impresoras 3D, con materiales compuestos de polímero (PLA) y polvos metálico (Aluminio). En primer lugar, se creó el filamento formado por una matriz de PLA y un refuerzo de ALUMINIO, el cual fue extruido en una máquina moldeadora fabricada dentro en el laboratorio de moldeo de este Instituto, tomando como consideración que el material de refuerzo en este caso aluminio serán los siguientes porcentajes 0% y 20%. Colocando estos filamentos en una impresora adecuada para la fabricación de piezas en 3D con materiales compuestos a las cuales se les realizó un análisis de experimentos para determinar qué porcentaje de material compuesto tiene mejores propiedades mecánicas.

**Filamento PLA, Material compuesto, diseño de experimentos (DOE)**

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## Introduction

Conventional manufacturing processes are based on the use of resources with a large capacity of control elements to achieve very high levels of precision and reliability. The use of computer systems in the design, manufacturing and simulation engineering phases of a product, in combination with other techniques based on mechatronics, have managed to raise production systems to high levels of efficiency Mesa María (2015). Within the manufacturing processes of a product, three groups of technologies can be distinguished, depending on the method of obtaining the required geometry:

– Conformative technologies: Molds or preforms are used to achieve the geometry of the part. This set encompasses all known molding techniques.

– Subtractive technologies: The specific geometry is obtained by removing material from a larger geometry. It includes techniques such as machining, EDM and cutting by water jet or laser.

– Additive technologies: geometry is obtained by adding material layer by layer according to a virtual 3D design, without resorting to molds and without removing material.

This research is focused on the use of additive technology, specifically 3D printing with composite materials, modifying the mechanical properties of the manufactured parts, generating knowledge that greatly contributes to the contribution of advantages in the field of education.

## State of the Art

At the Polytechnic University of Madrid, Technical School of Industrial Engineering, the aluminum castability study was carried out with models made in PLA by 3D printing, the objective of which is to obtain unique parts for prototyping or very small print runs per the casting process with lost models in polymers manufactured by 3D printing, a casting process basically consists of pouring liquid metal into a mold with the geometry of the part to be manufactured inside and its subsequent solidification and cooling.

To achieve this end, the traditional molding system (green molding and chemical molding) will be maintained. The main variant of the project is the replacement of the molds created from any material with the possibility of being machined (metal, wood, resins, waxes, among others) with the cost of tooling that entails and using 3D technology. In the study we proceed to the union of both technologies, 3D printing and the casting process, manufacturing a model in a polymer using a 3D printer. The manufacture of the models is carried out by the material deposition system from a coil Bustos Carolina (2016).

In the Department of Continuous Media Mechanics and Theory of Structures of the Higher Technical School of Engineering at the University of Seville, work was done on the development of an additive manufacturing system for composite materials, as well as the characterization of the material used. Said system is related to a 3D printer that allows the use of two types of materials: thermoplastic filament (nylon) and composite filament (fiberglass, carbon fiber and Kevlar). The novelty of the printer is the manufacture with fiber reinforcements, which allows obtaining parts with better rigidity and resistance properties than the usual ones obtained with printers for plastic materials Mesa María (2015).

In the Faculty of Biotechnology of the University of Liubliana in Slovenia in conjunction with the Faculty of Mechanical Engineering in Sarajevo, they are working on research related to the effect of the wood contained in the properties of the filaments used in 3D printing Mirko Kariz (2017).

## System Components

Polymer (PLA)

Polymers based on renewable or biodegradable resources are generating growing interest, both in society in general and in the plastics industry, as well as in the agricultural sector, since it would mean an outlet for their products towards different markets. Poly (lactic acid) PLA is a synthetic thermoplastic polymer from the family of alpha hydroxy acids or aliphatic polyesters derived 100% from renewable raw materials, which are produced from lactic acid Valero Manuel (2013).

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Lactic acid is produced by anaerobic fermentation of carbon-containing substrates, either pure (glucose, lactose) or impure (starch, mixtures) with bacteria and fungi. PLA molecules can be synthesized through a lactic acid condensation polymerization process at a temperature not less than 120 degrees Celsius. PLA is characterized by its good mechanical properties compared to other thermoplastic polymers (such as PET, the best-known thermoplastic polyester). PLA also has good barrier properties against odors and flavors, likewise it has high resistance to fats and oils, making it appropriate for packaging oils, dry and perishable products. PLA has been used in biomedical applications in drug-controlled release systems, thanks to its biodegradability. To improve the properties of PLA, it can be mixed with plasticizing agents, metals or other polymers.

Metallic powders

The metallic powders available for additive manufacturing are largely the same as those used in many areas of industrial application (such as: aerospace, automotive, medical devices, among others) Escorsa Enric (2017), such as: stainless steels, aluminum alloys, cobalt-chromium or nickel superalloys, pure titanium or titanium alloys, copper alloys, precious metals (gold, silver, platinum, palladium, among others), developments and current aluminum application patents are shown below : Anvil Semiconductors, uses aluminum (US2017018634A1) and Hamilton Sundstrand aluminum alloys and other metals (US2017016093A1); Hitachi (EP3118865A1) iron, aluminum and chrome alloys. UACJ Corp aluminum alloys that allow thermal bonding (EP13884783A).

## Methodology

As previously mentioned, PLA is a thermoplastic synthetic polymer derived from renewable raw materials that are produced from lactic acid. Its main advantages are that it is biodegradable, recyclable and compostable. In addition to saving energy since 25-55% less energy is required for its production compared to petroleum-based polymers Valero Manuel (2013). PLA is characterized because its mechanical properties are good compared to other thermoplastic polymers (such as PET).

In order to modify the mechanical properties of PLA, in this work it was mixed with aluminum metal powders and the process is described below.

Preparation and generation of the filament.

The research of the Faculty of Biotechnology of the University of Liubliana Slovenia Mirko Kariz (2017) was taken as a reference. In which a material with wood dust is manufactured, it began with the smallest combination 80 - 20 in which good results were not obtained, retaking this investigation and applying the Taguchi methodology of a $2^2$ Factorial design (see Table 1). The creation of the new composite materials has been carried out by means of the extrusion-composition of a filament with an approximate diameter of 1.75 mm extruded at a temperature of 175 °C, using 80 grams of PLA reinforced with Aluminum 20 metal powders as a base matrix. grams, for the generation of a composite material (see Figure 1).


**Figure 1** Mixture of PLA with metallic aluminum powder (80% PLA and 20% Al).
*Source: TecNM / ITN*

| | MA1(%) | MA2(%) | MA3(%) | MA4(%) |
|---|---|---|---|---|
| PLA | 100 | 80 | 90 | 95 |
| Aluminio | 0 | 20 | 10 | 5 |

**Table 1** Percentages of PLA and Aluminum
*Source: TecNM / ITN*

Manufacture of the 3D part with the filament made up of PLA and Aluminum

The composite filament with the aluminum metallic powder was placed in the Flash Forge Creator Pro 3D printer for the manufacture (at a controlled temperature of 21°C) of the 3D part to which the tests described in the following section were performed. The printing parameters configured in the printer are the following:

- Resolution: Standard.
- Layer height: 0.18mm.
- Height of the first layer: 0.27mm.
- Filling density: 100%.
- Pattern density: Line.
- Printing speed: 60mm/s.
- Travel speed: 80mm/s.
- Extruder temperature: 180°C.
- Platform temperature: 50°C.

In Figure 2, you can see the image of the part modeled in SolidWorks and manufactured in the 3D printer to which the stress tests were applied.

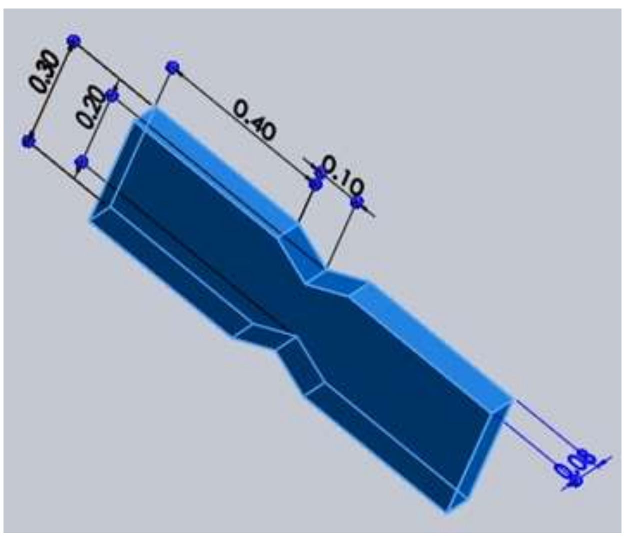


**Figure 2** Modeling of the part manufactured in the 3D printer with the composite material used for tension (inch units)
*Source: TecNM / ITN*

Figure 3 shows the image of the part modeled in SolidWorks and manufactured in the 3D printer to which the compression tests were applied.

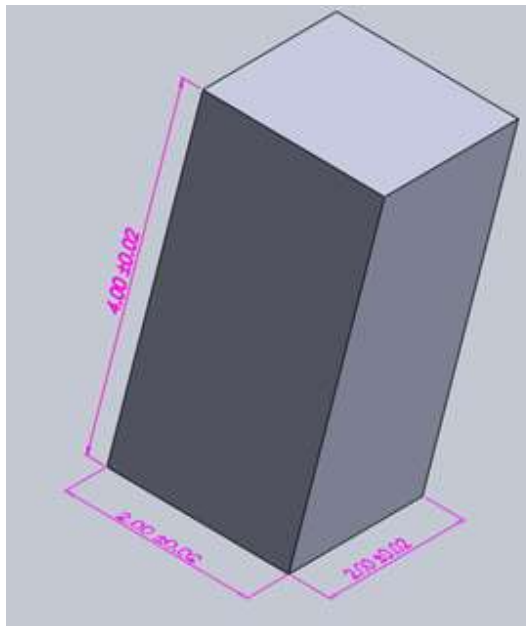


**Figure 3** Modeling of the part manufactured in the 3D printer with the composite material used for compression (inch units)
*Source: TecNM / ITN*

## Results

Tension and compression tests were carried out in a universal tension, bending and compression machine model: WDW-S5 (with traceability to CENAM and NIST) owned by the company Metrología y Pruebas S.A. de C.V. (MYPSA), as can be seen in Figure 4.

**Figure 4** Tension, bending and compression machine model: WDW-S5
*Source: MYPSA*

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Table 2 shows the result of the destructive tension test of 3 pieces created with pure PLA, the fracture point was in the center of the piece, which has a cross-sectional area of 0.016 in2 and the greatest effort was 6210 psi, on the specification sheet for this material gives us a maximum tensile strength of 7,000 psi.

| PLA puro (MA1) | | |
|---|---|---|
| P (LBF) | Area (in$^2$) | Esfuerzo (PSI) |
| 99.365578 | 0.016 | 6210.34863 |
| 87.67551 | 0.016 | 5479.71938 |
| 76.210251 | 0.016 | 4763.14069 |
| PLA-AL (MA2) | | |
| 76.43506 | 0.024 | 3184.79412 |
| 78.008723 | 0.024 | 3250.36346 |
| 76.210251 | 0.024 | 3175.42713 |
| PLA-AL (MA3) | | |
| 89.249173 | 0.016 | 5578.07331 |
| 59.799194 | 0.016 | 3737.44963 |
| 56.651868 | 0.016 | 3540.74175 |
| PLA-AL (MA4) | | |
| 94.41978 | 0.016 | 5901.23625 |
| 125.443422 | 0.016 | 7840.21388 |
| 84.5281842 | 0.016 | 5283.0115 |

**Table 2** PLA tension destructive test
*Source: Own Creation*

Tests were carried out with 3 pieces of PLA with Aluminum, in which the fracture point was in the clamping of the jaws, which has a cross-sectional area of 0.024 in2 and the maximum stress was 3250.36 psi, as can be seen in the Table 2 PLA-AL (MA2).

As can be seen, there was a degradation of the PLA and aluminum composite material; During the creation of the filament, in the printed pieces and the tension tests it was possible to observe that the pieces were very fragile.

Compression tests of pieces created as in Figure 3 were also carried out, in which they were printed according to the percentages in Table 1, the results of these destructive tests can be seen in Table 3, as can be seen as in the tension test there is a degradation of the material from the ultimate stress.

| **PLA puro (MA1)** | | |
|---|---|---|
| P (LBF) | Area (in$^2$) | Esfuerzo (PSI) |
| 334.066174 | 0.04 | 8351.65435 |
| 332.267702 | 0.04 | 8306.69255 |
| 335.415028 | 0.04 | 8385.3757 |
| **PLA puro (MA2)** | | |
| 314.282982 | 0.04 | 7857.07455 |
| 288.205138 | 0.04 | 7205.12845 |
| 326.422668 | 0.04 | 8160.5667 |
| **PLA puro (MA3)** | | |
| 348.903568 | 0.04 | 8722.5892 |
| 292.926127 | 0.04 | 7323.15318 |
| 229.529989 | 0.04 | 5738.24973 |
| **PLA puro (MA4)** | | |
| 333.616556 | 0.04 | 8340.4139 |
| 460.85845 | 0.04 | 11521.4613 |
| 339.911208 | 0.04 | 8497.7802 |

**Table 3** PLA compression destructive test
*Source: Own Creation*

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### Conclusions

Among the main objectives of this work is to generate knowledge in the area of composite materials and 3D printing, the tests carried out generated data that, when interpreted, we reached the following conclusions:

The filaments that were generated were 1.5-meter sections since the piece to be printed required that amount of material (1.1 m). The filaments made with aluminum powder when being processed we realized that they were more brittle than those of PLA alone. We came to the conclusion that it was due to an excess of reinforcing material (Aluminium), which functioned as a source of heat and degraded the material since the material's technical sheet gives us a melt temperature of 188 to 210 ℃, we handle it at 175 ℃ since We observed that the material was burning and coming out very liquid and must have a viscous consistency (melt temperature).

In the tests carried out, the highest stress was 6,210 psi. The specification sheet for this material gives us a maximum tensile stress of 7,000 psi (PLA in pellets for plastic injection molding). As it can be seen, the data is not very far from the maximum tensile stress of the PLA specification sheet used (we do not have any reference in 3D printing), we consider that the degradation was due to the high amount of aluminum metal powder. In the future, it is intended to carry out the same tests with smaller amounts of aluminum metal powder and we are comparing tensile strength given by the manufacturer of polymer for plastic injection molding. We hope to have a reference for 3D printing.

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