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EDUCATION & TRAINING

Monitoring an Analysis of Perturbations in Fusion Deposition Modelling (FDM) Processes for the Use of Biomaterials

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Abstract

During an FDM production process, there are different external disturbances to the characteristics of the machine that can affect to the production process. These disturbances will cause the final result differs from the desired one. Moreover, these disturbances, such as temperature or chamber humidity, are extremely important in case of using biocompatible materials. The use of these kind of materials with not controlled environment, can cause them to modify or loss of their properties; what will make the product unusable. Apart from these external disturbances, the conditions of the machine to which the material is subjected must also be considered, such as temperature, vibrations or extrusion speed. The monitoring of all these data will allow to know the conditions to which the product was exposed during the process. In this way, it will be able to verify the validity of the final product. For these reasons, the purpose of this work is to monitor the conditions of production of structures with biocompatible materials by fused deposition modelling (FDM) technique. This monitoring will allow us to obtain a report that guarantee the technical and geometrical characteristics of the model and the biomaterial properties. The parameters chosen to be monitored are: Diameter of filament use, temperature in extrusion nozzle, ambient temperature in closed chamber, ambient humidity in closed chamber. The obtained results, after collected and analysing the data, present variations of up to 3% in the temperature of the nozzle of the extruder with respect to set temperature. In the case of the filament diameter the difference with respect to the value provided from the filament supplier is of 13,7%. In addition, the results show how the ambient humidity in closed chamber has changed by 2 percentage points and the ambient temperature in closed chamber has been increased 6,52 °C with respect to the set values.

Keywords Additive manufacturing process · Biomaterials · Sensor · Medical application

Introduction

The reduction of costs and production times in various industrial sectors is due to the attention of the engineering world paid to improve the quality of products and services with the optimization of industrial processes [1, 2]. In the case of medical application, this has allowed to improve the performance of materials used for prosthetic implants in the case of knee [3]

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and hip joint [4, 5] or in the case in which the aims was to study and optimize the tribological performances of the human joint implant materials [6, 7]. In this last case, in recent years, the optimization of the performance of biomedical products has been made possible also by scientific studies on the simulation of the dynamic behaviour of human joints [8, 9]. Particular attention has been paid to the geometric parameters used in the implementation of the mathematical models developed. Among these, for example, the algorithms for the morphometric fit of the bone surfaces that form the tribological contact of the ankle human joint [10]. The same techniques and procedures, in recent years, have been adapted and improved to be applied in Finite Element Modelling (FEM) analyses of the dynamic behaviour of soft tissues, such as tendons, ligaments, fibrous tissues, synovial membranes (which are connective tissue), and muscles, nerves and blood vessels that form the human joint [11, 12]. The same happened in the case of biomedical products printed in 3D such as the splints for arms or legs for people who had suffered fractures or specific diseases, such as rupture of the Achilles tendon [13]. In fact, a perfect geometric modelling and knowledge of the morphometric parameters of the limbs to be immobilized, has allowed to optimize and improve the production and 3D printing of the customized product. This is thanks to the development of additive manufacturing processes such as 3D printing [14]. This is thanks to the development of additive manufacturing processes such as 3D printing. In fact, the new layered additive manufacturing techniques have come to be recognized as the fourth industrial revolution. The increase in manufacturing at a particular and professional level requires an increase in print quality, a reduction in machine costs and an increase in the knowledge of the scientific community [15–17]. Still in the medical field, the application of engineering applied to sectors related to human health has allowed the development and production of hospital equipment. During the deposition process, many of the variables that contribute to improving or worsening the final result are subject to disturbances that come from the system itself as well as from others outside the machine. This type of deviations is difficult to control, as happens with the variability of the material, variations in the outside and inside temperature of the machine, humidity or deviations in the printing area [18]. All these variables, like temperature, humidity, vibrations etc. will affect to increment or decrement the different forces of adhesion and cohesion between the layers of the same material, but also when working with different materials [19, 20]. Currently, the sensorized and the control of additive manufacturing processes, is presented as an evolution of the methods, categorized as sensorized and control of the variables and sensorized and control of manufacturing attributes [21]. Most of the cases, the disturbances produced during the process are assumable with a post processed so that the final product can be fully functional. However, when the material employed is a biomaterial or a biocompatible material, it is necessary to control during the whole process the conditions in which the structure is formed. It will make possible to discriminate and analyse zones that may have been affected by these variations and, consequently, it will make possible to make decisions about the validity or rejection of the final object. In this paper, it will be showed a data collection system for temperature, humidity and filament diameter, during the process in a fused deposition machine for the subsequent obtaining of reports on the conditions in which the piece has been produced. In addition, this methodology is presented as a low cost system that could be installed on any FDM machine with similar characteristics.

Materials and methods

First point in the study, was carried out by collecting measures of different parameters, maintaining the focus on two specific goals [22]:

- Study how the different production conditions affect the final structure.
- Evaluate the realization of a control over these data, in order to guarantee the optimal conditions during the realization of a structure with biocompatible characteristics.

To do this, the following parameters have chosen to be monitored:

- Diameter of filament used
- Temperature in extrusion nozzle
- Ambient temperature in closed chamber
- Ambient humidity in closed chamber

Diameter of filament used

Filament diameter is of great importance to be considered due to its variations in the manufacturing process that can cause the final result to vary notably. Although manufacturers and researches try constantly to improve the polymer manufacturing process, including spinning and injection moulding., The product quality and efficiency are influenced by multiple processing parameters and materials, such as nominal cutting and shearing, the temperature of the process or the branch, that currently are not fully understood. The control and optimization of such operations contribute to getting closer and closer to the nominal size of the filament, but it still moves in quite large tolerances [21, 23–25]. It was analysed the diameter fluctuations of different FDM plastic providers. There were taken samples of a length of 3 m of filament each centimetre, by using a sensor with a resolution of 0,01 mm. Four brands were analysed with a nominal diameter of 1,75 mm, and the results are shown in Fig. 1.

Fig. 1 Diameter fluctuations of 4 different filament providers

Analysing these samples, it comes up hat the diameter quality is very low. It varies from 1,56 to 1,86 mm, see Table 1. It is due to that the manufactures normally check the diameter with a lower frequency and get the medium value as quality test.

With these data, it is possible to calculate the variations of volume deposited during the process of extrusion:

$$volume = \pi * radio^2 * length$$

Analysing a length of 10 mm of filament, the variation of volume deposited can varies up to 33.51% of the nominal value (Table 2).

These data can explain the reason why the produced models use to have defect parts as a volume higher than the theoretical model or a lack of material in some layers. The deposited material not only affect to the dimensions and mechanical characteristics of the piece and the exterior finish, it can also result in discomfort or friction in the case of being in contact with the skin. In Fig. 2 it is possible to check the error that appears when producing a piece of thickness 1 mm with two portions of filament of average 1,73 mm and 1,82 mm in diameter [22].

Extruder temperature

For a correct extrusion process, it is necessary to get and maintain an optimal nozzle temperature. If the temperature achieves high values, the material will change its properties, even changing to a crystalized state that will ruin the model and even the nozzle. In case that the temperature was just some degrees higher than the optimal, the expansion of the material will not be constant, therefore the final dimension will be wrong.

Other way, if the temperature is lower than recommended for a specific material, the adhesion between layers will not be correct and it will appear breakpoints. These breakpoints are not visible, so it is of high importance to take care of this problem, as it could produce a higher problem during the use of the part.

Table 1 Sampled data analysis

Brand	Maximum [mm]	Minimum [mm]	Average [mm]
1	1,86	1,57	1,78
2	1,80	1,68	1,76
3	1,82	1,58	1,67
4	1,83	1,56	1,73

Table 2 Volumes deposited in 10 mm of advance

Diameter	Volume [mm^3]
1,75 mm (nominal)	24,05
1,56 mm (minimum)	19,11
1,86 mm (maximum)	27,17
1735 mm (average)	23,50

Chamber temperature and humidity

Similar case happens with the chamber temperature. A correct and controlled atmosphere of temperature and humidity, will guarantee the correct adhesion between the layers, and the properties of the final produced part.

In case of using biomaterials, the importance of controlling this temperature and humidity is even greater, as it could lose it biomaterial properties [19].

Results and discussions

After studying the different parameters that can interfere in the final structure, it is proceed to collect data in a real process. It will be taken samples of extruder and chamber temperature, humidity and filament diameter. Apart of these data, it will be stored the coordinates X, Y and layer of all the samples. This will allow us to check the conditions of the deposited filament in all the zones of the structure.

Measurements are collected during a real production process and are obtained the following data, showed in Figs. 3, 4, 5, and 6. The measurement of each one of the sensors has been collected every 30 s for 74,5 min, obtaining a total of 149 samples [22].

- Extruder Temperature

As can be seen, the extrusion temperature is not at all constant, due mainly to variations in the air flow of the fan of the nozzle, which, by influencing the surface of the piece being made, varies constantly according to the geometry of it, making it difficult to control.

- Chamber temperature

The temperature in the chamber increases during the process, due to the heat that comes from the nozzle, the deposited material and the machine itself (both electronics and mechanics).

- Chamber humidity

Fig. 2 Error due to filament diameter variations

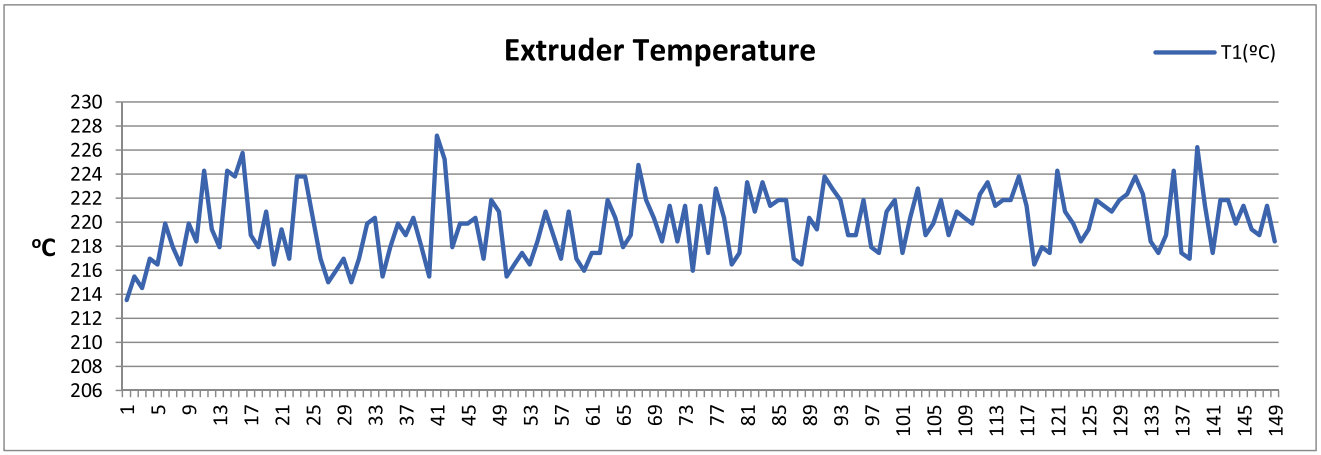

Fig. 3 Extruder Temperature

The humidity decreases slightly during the process, due to the increase in temperature of the chamber.

- Filament diameter

The filament diameter varies greatly, reaching maximums of 1,94 mm and minima of 1,64 mm.

In many cases, strict control of the temperature or humidity in the printing chamber is needed. In the case of

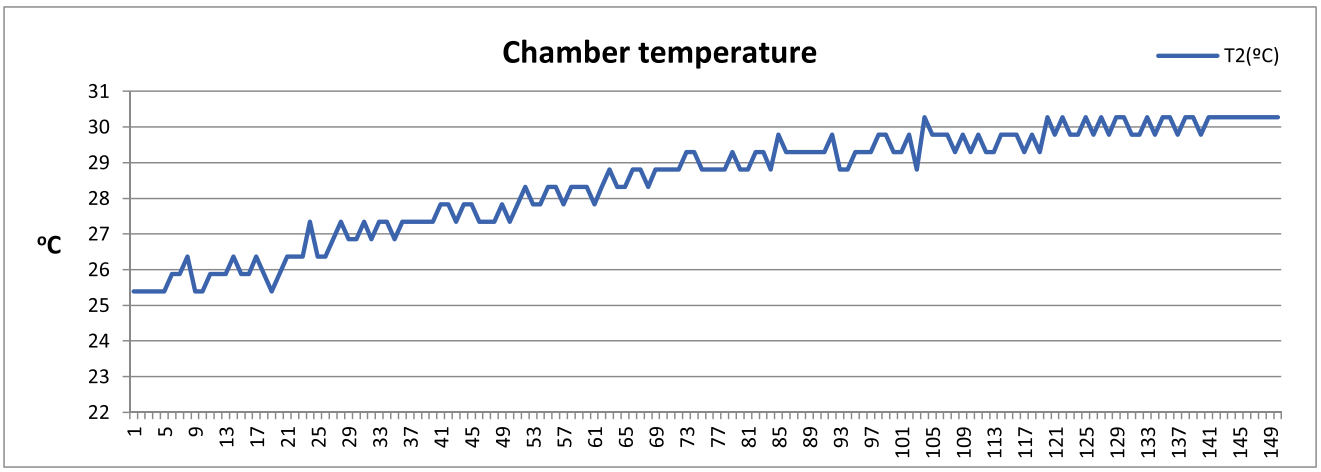

Fig. 4 Chamber temperature

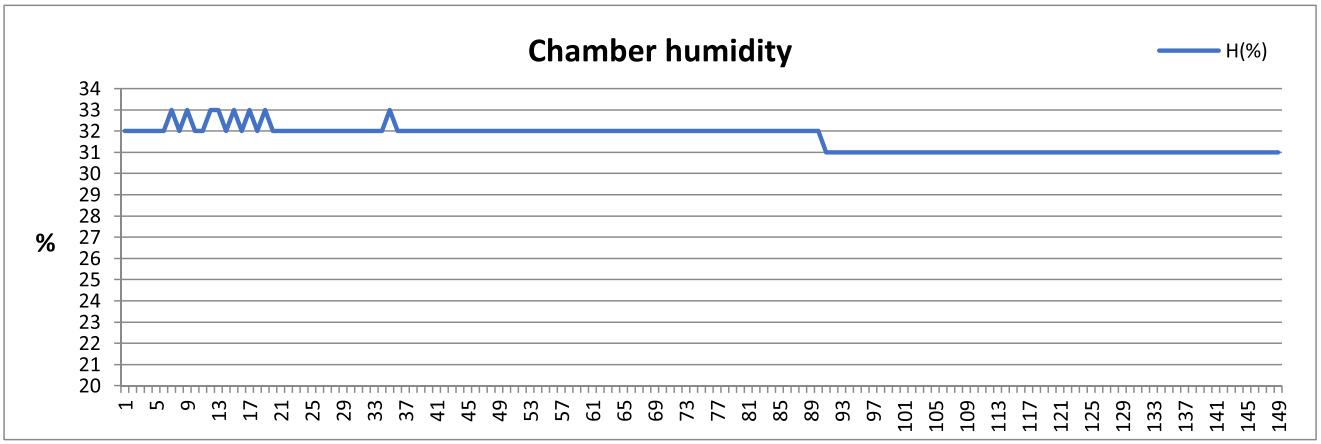

Fig. 5 Chamber humidity

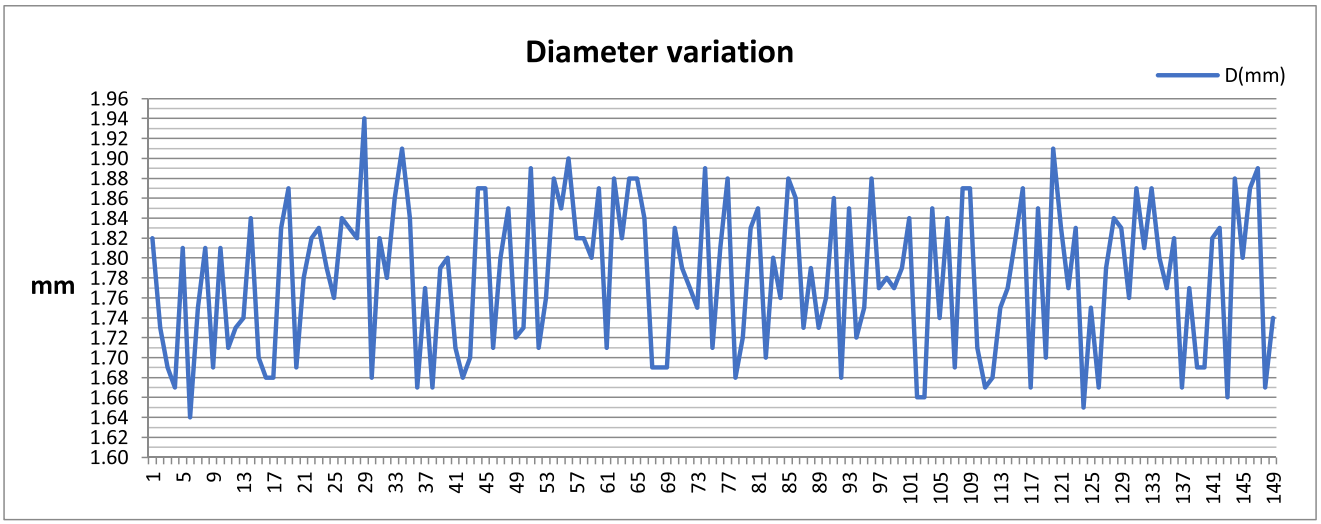

Fig. 6 Filament diameter

manufacturing by 3D printing bio-ceramic joint implants has to be performed at low temperature. The fluctuation of the temperature would damage the internal structure of the material. In other cases, the temperature could produce novice particles. This would affect to the operator safety and would make impossible to use the machine in some cleaning rooms that are normally used in medical ambient [26].

After analysing the data and obtaining the results shown in Table 3, there are variations of up to 3% in the temperature of the nozzle or 13,7% in the diameter. In addition, the humidity has changed by 2 percentage points and the ambient temperature has been increased 6,52 °C:

Conclusions

In this study a low-cost system that allows to analyse how much the optimal parameters for a good FDM production part, can change during the process, has been developed. In fact, the disturbances external to the machine and the process, but

Table 3 Analysis of collected data

	Humidity (%)	Chamber temperature [°C]	Extruder temperature [°C]	Filament diameter [mm]
Nominal	*Not controlled*	*Not controlled*	220	1,75
Average	31,64	25,56	218,28	1,78
Maximum	33,00	34,67	227,20	1,96
Minimum	31,00	19,04	213,53	1,61

also intrinsic from the machine or the process can affect the 3D manufacturing of the part.

As expected, the data obtained from these disturbances are really far to be constant; furthermore, the variation is produced during all the process, without reaching a stable value. With the present study has been possible to analyse different materials, different brands of the same material, in order to see that the manufacturer shows the optimal conditions for a correct printing. However, it is impossible to maintain these conditions with this production system implemented in these kind of machines. It would be necessary to develop an upgrade of the machines to reach this target.

From this point, there are two clear lines of investigation. First of them, implementing a system that can measure the disturbances and achieves the goal of correct them. The second one, implementing a system that gets this type of data during the process, what will make possible to compare with the optimal.

The control of environmental conditions for 3D printing is of fundamental importance in biomedical applications.

In addition, it is intended to complement the measures already obtained with others such as:

- Extra temperature sensors: In different areas of the chamber, which will allow detecting the different temperatures in the different zones to try to control the air flow.
- Vibrations: It will allow detecting errors in the deposition of the material. Also in the future it would be possible to try to correct them.
- Deposition speed: It will make possible to do the filament deposition on an accurate way speed and together with the measurement of the diameter, it will allow to calculate the volume of material deposited at each moment.

The set of all these measures will give us a full report of the conditions that occur during the process, in addition to help to correct them.

Compliance with Ethical Standards Fernando Blaya Haro declares that he has no conflict of interest. José María de Agustín del Burgo declares that he has no conflict of interest. Roberto D'Amato declares that he has no conflict of interest. Manuel Islán declares that he has no conflict of interest. Enrique Soriano Heras declares that he has no conflict of interest. Jesus Manuel Garcia Alonso declares that he has no conflict of interest. Juan Antonio Juanes Mendez declares that he has no conflict of interest.

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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