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Experimental Research on the Fabrication of Modular Devices for Drilling Using PLA for Model Parts

Diana Băilă[1], Remigiusz Łabudzki[2], Igor Fodchuk[3], Mirian Bonilla[4]

[1]Department Manufacturing Engineering, National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
[2]Department of Technology Planning, Poznan University of Technology, Poznań, Poland
[3]Department of Solid State Physics, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine
[4]Edibon International S.A., Madrid, Spain
Email: baila_d@yahoo.com, remigiusz.labudzki@put.poznan.pl, i.fodchuk@chnu.edu.ua, mbonilla@edibon.com

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Abstract

The objective of the work is to determine the influence of the PLA melting temperature during 3D printing on the dimensional accuracy of the model parts. Two modular drilling devices were also made using PLA model parts. The model parts were 3D printed using FDM technology and the ZMorph 2.0 hybrid 3D printer. The accuracy of 3D printing of the model part influences the realization of modular devices. In recent years, technology has evolved a lot, and the need to have the most efficient manufacturing equipment has increased. This is the reason for the development of 3D printers using FDM technology for plastic parts. The software used by these 3D printers used in FDM technology is very sophisticated, as they allow the manufacture of very precise 3D prototypes, identical to the designed 3D model, through modern additive manufacturing techniques. The quality and mechanical strength of the prototypes obtained using 3D printers is very good. The materials used by the 3D printers manufactured by FDM are cheap and accessible. These 3D printers are used to make three-dimensional objects (gears, flanges, bearings, covers, casings, mechanisms, figurines, interior and exterior design elements, architectural models, medical models).

Keywords

Modular Device, 3D Printer, FDM-Fused Deposition Modeling, Dimensional Accuracy, Melting Temperature

1. Introduction

An orientation and fixation device represents a set of organological groups, ordered according to a plan, in which informational, energetic and material flows are present, and which aims to orient and fix the semi-finished part in certain technical-economic conditions. These organological groups must be designed, made and assembled. The use of modulated manufacturing equipment presupposes the existence of a set of modulated elements, physically existing, from which this manufacturing equipment is made by assembly. The modules in the composition of a set meet well-defined conditions in terms of durability, precision, the possibility of assembly, and the possibility of adjustment. The Zmorph hybrid 3D printer prints 3D using FDM technology. Fused Deposition Modeling (FDM) technology uses a wide range of materials such as PLA, ABS, nylon, etc. The mechanical resistance of the parts is very good, and often, the current 3D printers that are sold have 3D printed components in their composition. 3D printing with FDM technology is based on the materialization of a CAD product by adding successive layers. The object model is saved in the stl file, so that it can be used by the 3D printer software [1]-[4].

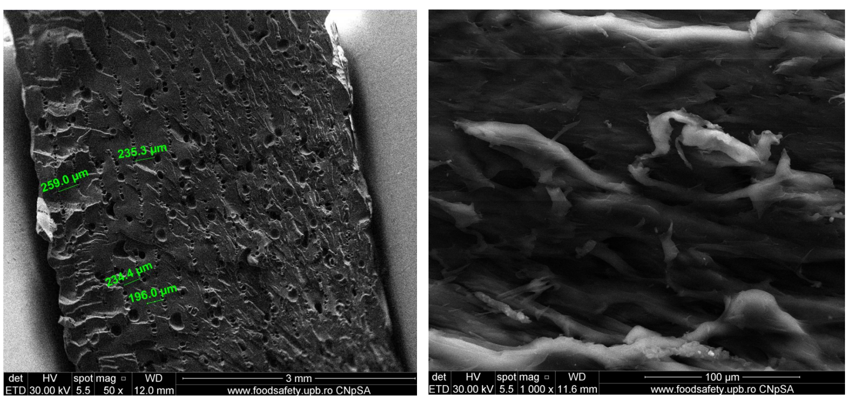
Within this technology, it is necessary to build support for certain types of parts.

Prototypes made by FDM technology do not require additional post-processing treatments and can be used immediately, presenting a special surface quality.

Rapid prototyping technology (as FDM, SLA, DMLS, SLM) helps identify potential problems that may arise in the design and conception process, respectively to realize complex parts with special mechanical properties [5]-[8]. With a prototype, you can see for real if two surfaces are joining correctly or if the joining points are aligning as they should.

Hybrid 3D printers are multifunctional printers that will replace traditional 3D printers, namely CNCs, in the future and will be found in most households due to their very varied functionality. The hybrid 3D printer necessities calibration processes before starting the 3D printing process.

Figure 1 shows 3D printed prototypes using the ZMorph 3D printer, using PLA.



(a) (b)

Figure 1. SEM analysis of the rupture of PLA (polylactic acid) cubes in atmosphere. (a) ×50; (b) ×1000.

This printer can print layers down to 50 microns. The Zmorph hybrid 3D printer is equipped with numerous interchangeable heads allowing the printing of a wide variety of materials. The manufacturing dimensions of the 3D printer are 300 × 235 × 165 mm. The materials used by this hybrid printer are very diverse from PLA, ABS, PET, PEEK, and PEKK special filaments. The software used by this printer is Voxelizer. This software permits to visualize the virtual 3D parts, and to prepare the 3D printing process, to choose the scale, the materials, the 3D printers, the fabrication parameters, and the supports, then the parts will be saved as gcode file to permit the 3D printing process [1]-[4].

2. Experimental Research

2.1. The Rheological Behavior of PLA-Type Thermoplastic Materials in the Melt

Synthetic polymers are well known for their diverse applications in a wide range of fields, in the form of plastics, elastomers and fibers.

The deformation whose value increases continuously and does not recover after removing the force is called flow.

Fluids offer little resistance to deformation, and the forces of internal friction, which arise during flow, reduce the speed of deformation.

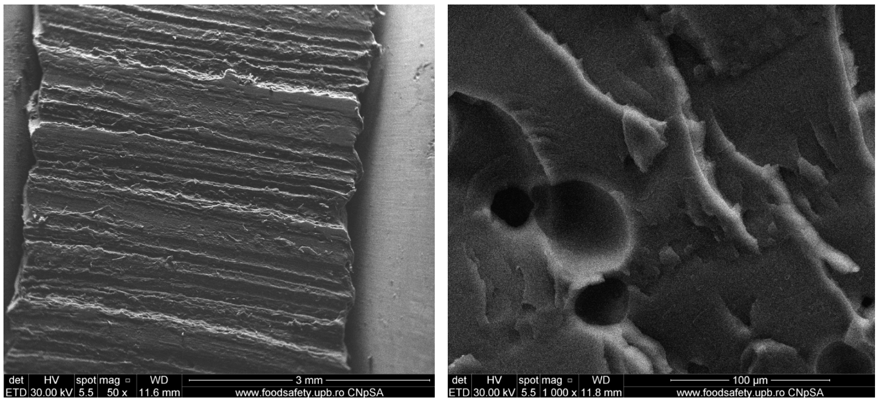
Under the action of a force, the rate of deformation of fluids increases until equilibrium with the frictional force is established, after which the rate of deformation remains constant. Flow is a key process in most operations specific to the synthesis and processing technologies of macromolecular compounds. The appeal to rheology is indispensable given its contribution to the elucidation of the flow behavior of various systems formed by macromolecular compounds.

Polylactide (PLA) has been intensively researched and used as a biomedical material, due to its high biocompatibility, good biodegradability in the human body, as well as excellent rheological and thermal properties and good molding properties. PLA has high mechanical strength.

It is also frequently used in industry. Looking at the rheological properties of PLA, the variation of the linear viscoelasticity range between 0.001 and 10 Pa was established. The crystalline melting enthalpy for PLA is considered to be 93.0 J/g. **Figure 1** shows the SEM analysis of the rupture in normal atmosphere of the PLA disc manufactured by FDM and can remark the porosities between 196 - 259 μm, specific of FDM technology.

Figure 2 presents the SEM analysis of PLA after the traction test in liquid nitrogen, remarking the parallel fibrous structures, and fracture defects due to the brittleness induced by the cryogenic conditions.

The rheological behavior of real fluids and therefore of thermoplastics is presented in rheograms that reproduce the dependence between the unit shear stress and the re-slope $\dot{\gamma}$ (velocity gradient). These rheograms are obtained from simple fluid shear experiments. The curves $\dot{\gamma} = f(\tau)$ are called fluidity curves. Starting from these curves, the viscosity at each point of the curve can be calculated.



(a) (b)

Figure 2. SEM analysis of PLA after the traction test in liquid nitrogen. (a) ×50; (b) ×1000.

Rheological behavior is influenced by temperature, deformation time scale, molar mass and molar mass distribution, polymer structure. The re-slope of PLA differs depending on temperature as follows, presented in **Table 1**.

Table 1. Re-slope of PLA differs depending on temperature.

Temperature (˚C)	Shear strain rate (1/s)
180	0.32
185	0.33
190	0.35

The viscosity of polymer melts is influenced by molar mass, temperature, pressure, additives. The viscosity of the melts depends on the temperature, with great importance on the technological properties of the polymer, because the sensitivity of the viscosity to the temperature determines not only the choice of the processing regime but also the quality of the obtained products. With the increase in temperature, the possibility of the macromolecule passing from one equilibrium state to another occurs due to the activation energy. The dependence of viscosity on temperature can be expressed by the exponential equation depending on the activation energy of viscous flow.

$$\eta = A * \mathrm{e}^{-\frac{E}{R*T}}$$

A—frequency term;

R—gas constant;

T—temperature;

E—activation energy.

For a constant frequency of 1 Hz, it gets $\eta = 58.68$ kJ/mol.

The flow index (melt index) is a quantity that characterizes the flow behavior of different polymers in the molten state. The determination is made on apparatus at a certain temperature and pressure, for the amount of plastic material that flows through an adjustment (capillary), in a certain determined time (generally 10 minutes). In practice, the flow index lc is used as a basis for choosing the processing method. **Figure 3** shows the variation of PLA viscosity as a function of temperature, and it is noted that as the temperature increases, the viscosity also decreases. Since in the case of FDM processing, the PLA filament is melted, and the printer can be programmed according to the temperature of the melt used. Looking at the experimental part, the influence of the melting temperature on the dimensional precision of the cubes made was determined.

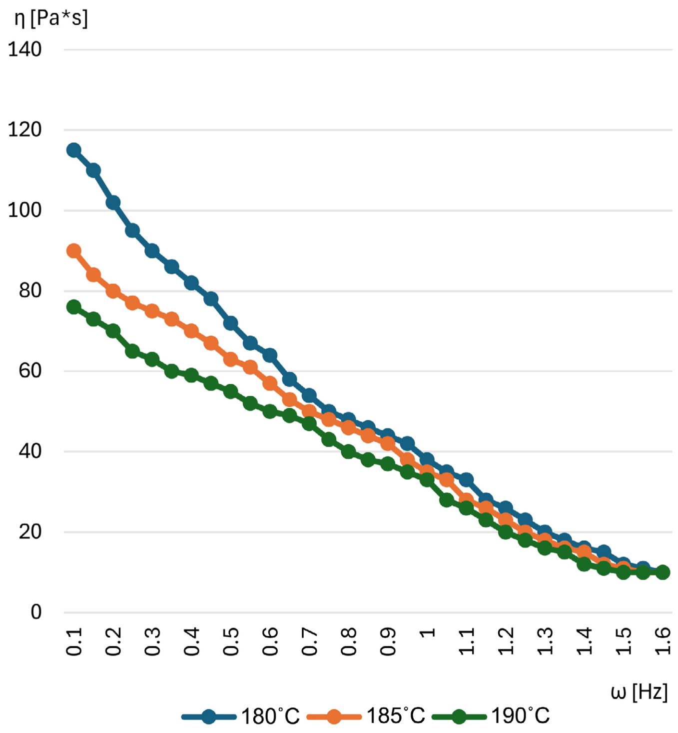


Figure 3. Variation of PLA viscosity with temperature.

Nine cubes with a side of 7 mm were designed in SolidWorks software. Using the ZMorph 3D printer's Voxelizer software, the stl file was converted to a gcode file to enable 3D printing. A nozzle with a diameter of 0.2 mm was used for processing, as in **Figure 4**.

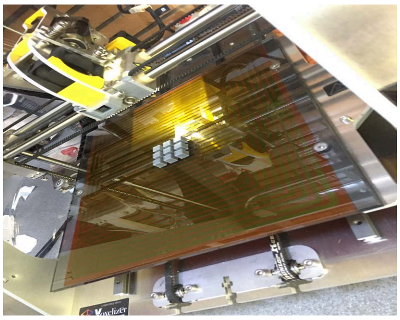


Figure 4. 3D design of the 9 PLA cubes.

The melting temperature varied between 190˚C to 220˚C (in each 5˚C) and several batches of parts were made. The temperature was determined and controlled grace of the Voxelizer software and of LCD of the 3D printer. For control, the precision was used a digital caliper, with a precision of 0.02 mm, and resolution of 0.01 mm.

It was noted that the optimal dimensional accuracy is at the temperature of 200˚C, in the event of an increase in temperature, the viscosity of the material decreases and it flows faster through the nozzle hole, leading to oversizing of the parts.

At a temperature lower than 200˚C, the viscosity increases and in this case the flow through the nozzle hole is slower, so under-sizing of the parts will occur.

Figure 5 shows dimensional accuracy variation on the OX axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

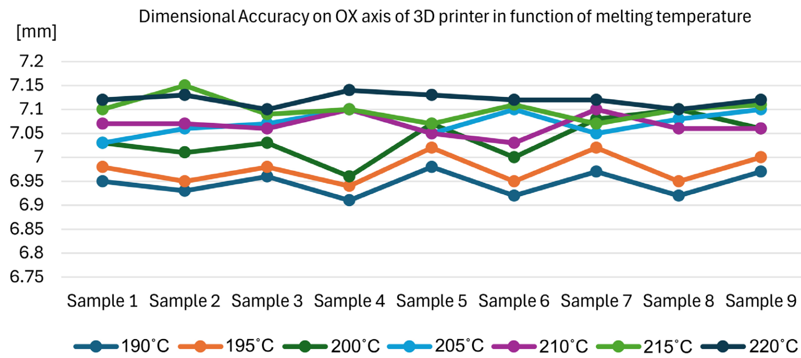


Figure 5. Dimensional accuracy variation on the OX axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

Also, the quality and hardness of the parts' surfaces are influenced by the melting temperature variation.

It is noted that the best dimensional accuracy along the OX axis, for PLA, is found at the melting temperature of 200˚C.

Figure 6 shows dimensional accuracy variation on the OY axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

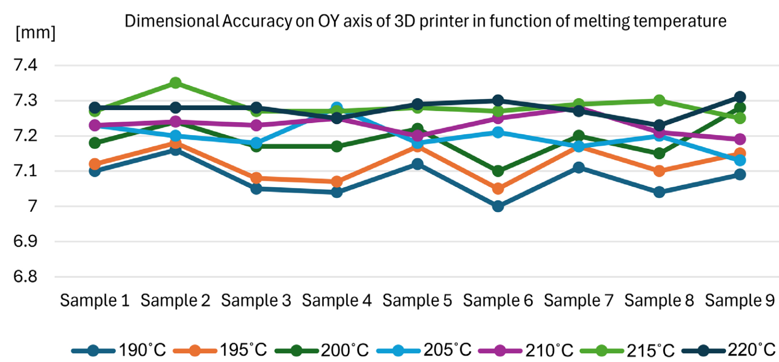


Figure 6. Dimensional accuracy variation on the OY axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

Also, the best results regarding dimensional accuracy for PLA are at the temperature of 200˚C.

An important influence on the dimensional accuracy is the calibration of the table, respectively the working temperature of the table, respectively bringing the 3D print head to zero. In this paper, it was established the accuracy of the 3D printed parts on, all 3 axis, because can influence the assemblies modular devices, and respectively the drilling manufacturing processes of the metallic parts.

It is also recommended that during the 3D printing of the parts used in the industry, they should be made using supports, in order to present a good quality of the surfaces of the processed part, of the dimensional precision and not to reduce the part dimensionally on the OZ axis. The print head must not press into the mass, because there is a risk of missing 1 - 2 layers of deposition, in addition, mass tensions may occur.

Filament deposition takes place in a zigzag pattern to reduce auxiliary times. In Figure 5, it is noted that the dimensional accuracy is low around 6.6 µm, because the print head presses on the mass, is not well adjusted and positioned at the zero position, and the mass is not well calibrated.

Figure 7 shows the dimensional accuracy variation on the OZ axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

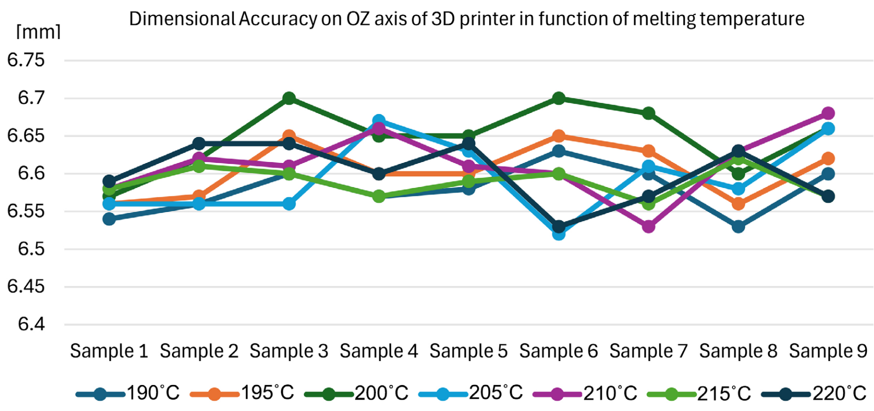


Figure 7. Dimensional accuracy variation on the OZ axis in function of PLA melting temperature, in the case of the ZMorph 3D printer.

To increase the mechanical strength of the PLA, reinforcements can be made with various metal or wood grains.

2.2. Design and 3D Printing of Model Parts

The prototypes for the gearbox parts were made according to the dimensions existing on the execution drawings.

The parts were designed in Inventor, SolidWorks and saved stl as in Figure 8.

The choice of the parameters of the 3D printing regime is made using the Voxelizer software, as in Figure 9. The accuracy of the 3D printed parts (the gearbox and the flange) is very important to realize the modular device assemblies for drilling process, to permit a precise orientation and fixation of the parts in the device, that influence the next manufacturing processes.

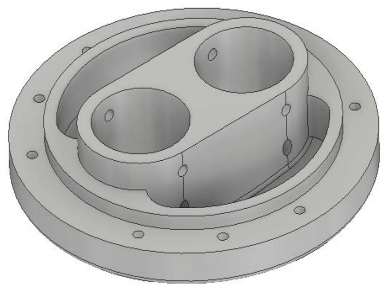


Figure 8. Stl file of gearbox.

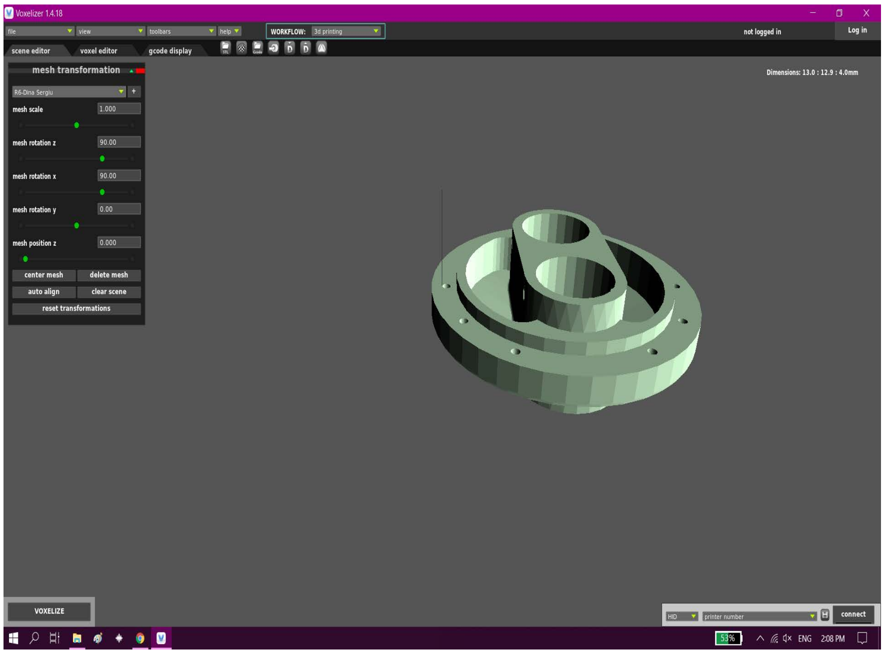


Figure 9. Choosing the parameters of the manufacturing regime through FDM technology, using the Voxelizer software.

Figure 10 and **Figure 11** show the 3D prints of the prototype of the gearbox, respectively of the flange, using PLA filaments.

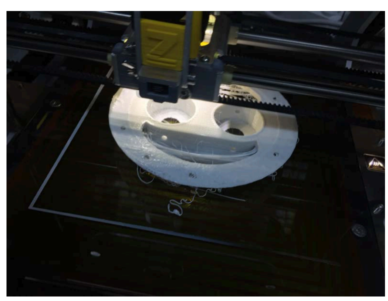


Figure 10. Gearbox prototype of PLA made by FDM using Zmorph 2.0SX hybrid 3D printer.

Figure 11. Flange prototype of PLA made by FDM using Zmorph 2.0 SX hybrid 3D printer.

2.3. Modular Devices Assembly

Modular devices use model parts made of plastic mass to allow modular elements to be assembled to build them, being used in drilling machine building, for precise metallic prototypes manufacturing. These model parts greatly facilitate the construction of modular devices, but the dimensional accuracy of the model parts is very important for the choice of orientation and fixing elements of the devices.

The parts are designed in the 3D Inventor software, the optimal orientation and fixation scheme is established, orientation errors, fixation forces and fixation errors are calculated. Modular devices are designed using steps. Afterwards, the explode is made to visualize the component elements for assembly.

In this case, two modular devices were made, for the operation of drilling the Gearbox, respectively the Flange, as in Figure 12 and Figure 13.

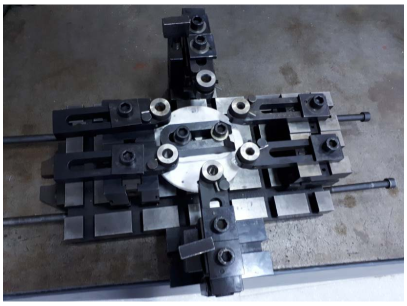


Figure 12. The modular device for the drilling of gearbox.

Figure 13. The modular device for the drilling of flange.

3. Conclusion

Modular manufacturing equipment provides users with a very powerful tool in solving one of the most acute problems, flexibility in the field of product manufacturing. The accuracy of the 3D printed model parts has a great influence on the assembly of the drilling modular devices. This is achieved by: 1) shortening the duration of the production of the modulated manufacturing equipment, in relation to the special ones (design stages, preparation of the execution technology, material and technological preparation, execution are not necessary); 2) the possibility of making orientation and fixing manufacturing equipment for parts very different in size, shape, processing operations.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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