25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COBEM2019-1976
EFFECT OF INFILL AND NUMBER OF PARTS PER CYCLE ON MECHANICAL PROPERTIES OF EXTRUDED PLA BY ADDITIVE MANUFACTURING

Igor Cesar de Carlos Rosa[1]
Giannini Barcellos de Oliveira[2]
Arthur Alves Fiocchi[3]
Diego Augusto Costa Alves[4]
Alexandre Zuquete Guarato[5]
Núbia dos Santos Saad[6]
Universidade Federal de Uberlândia. Av. João Naves de Ávila 2121, Câmpus Santa Mônica, CEP 38408-100, Uberlândia, Brazil.
[1]igor_cesarcr@hotmail.com, [2]giannini-jm2@hotmail.com, [3]arthurfiocchi@ufu.br, [4]diegoaugusto@ufu.br, [5]azguarato@ufu.br, [6]nubia@ufu.br

Abstract. *The dissemination of low-cost machines and the lack of standardized information and scientific approach can make Additive Manufacturing (AM) process variables directly linked to lower reliability and lack of understanding of the mechanical behavior of parts fabricated by AM. The understanding of these input variables is necessary for the overall knowledge of the results of quality and mechanical properties. The deposition of material layer by layer, popularly known as 3D printing, is then a vast field for scientific investigations. The present work aims to determine the mechanical properties of extruded PLA thermoplastic by means of three-point bending tests. The AM input parameters investigated were (a) percentage (P = 0 %, 10 %, 20 %, 30%) of the hexagonal (H) infill of the parts and (b) number of printed parts per manufacturing cycle (2 and 3 workpieces). The results show that increasing the percentage of infill improves the mechanical properties. The manufacture of more than one part per AM cycle modifies the mechanical properties. Among the groups studied the Ultimate Flexural Strength (UFS) increased for the smaller groups. Future specific technical standards for mechanical testing must take into account geometry and cross-sectional area of parts with infill lower than 100 % as well as the number of parts printed per cycle.*

Keywords: *Additive Manufacturing; 3D printing; Infill Percentage; Pieces per cycle; Three-Point Bending Test.*

1. INTRODUCTION

Developments in additive manufacturing (AM) processes began in the 1980s, but in recent years the offer of new technologies, scientific research and the market have had rapidly increased. The AM by thermoplastic extrusion is the most widespread technique, including in the domestic market (Balletti, Ballarin and Guerra, 2017). Extrusion technology and thermoplastics have been facing significant price reductions (Bourell et al., 2017, Levy et al., 2003, Stansbury and Idacavage, 2016).

The plastic raw material, traditionally filamentous, is selectively fused, extruded and deposited layer by layer, until the final object is completed (Fig. 1) (Stansbury; Idacavage, 2016). Among the diverse and growing types of thermoplastics, the following stand out: acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) (Stansbury; Idacavage, 2016; Chacón et al., 2017; Eyers and Potter, 2017). PLA has been gaining space due to the lower melting temperature (Tm) (average Tm = 190 ºC, 130 ºC < Tm < 243 ºC, Matweb, 2019) than ABS (average Tm = 222 ºC, 180 ºC < Tm < 274 ºC, Matweb, 2019), besides being biodegradable, recyclable, and biocompatible (Franco et al., 2016). Mechanical properties values of extruded PLA according to Lanzotti et al. (2015) are presented in Table 1.

One drawback of this kind of extrusion technique is associated with need of thermoplastic with specific viscosity. Besides that, in some cases support material has to be removed from the part at the end of manufacturing process (Stansbury; Idacavage, 2016; Eyers; Potter, 2017).

Table 1. Typical ranges of mechanical properties for PLA
Materials fabricated with FDM technology (Lanzotti et al., 2015).

Properties	PLA
Tensile strength (MPa)	15.5-72.2
Tensile modulos (GPa)	2,020-3,550
Elongation at break (%)	0.5-9.2
Flexural strength (MPa)	52-115.1
Flexural modulos (GPa)	2,392-4,930

Although there are many manufacturers of 3D printers of thermoplastic extrusion focused on the production of prototypes, parts, and mechanical assemblies, scientific studies in the field are still incipient, and various aspects of the process need clarification. It is also worth mentioning the constant development of new thermoplastics and their composites. The wide range of process parameters, materials, and printers paved the way for technological and scientific researches to better understand the mechanical performance of components manufactured by AM. At the moment there are still many uncertainties regarding the static and, mainly, dynamic mechanical behavior of parts produced by three-dimensional polymer extrusion (Singh et al., 2017; Brian et al., 2014).

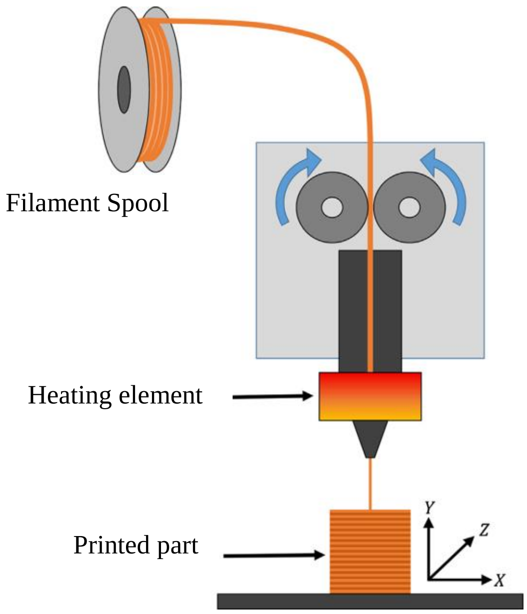

Figure 1. Schematics of thermoplastic extrusion (Stansbury; Idacavage, 2016).

The ASTM and ISO standards available for determination of mechanical properties of polymers were not developed taking into account that some AM processes allow to introduce internal voids that decrease real cross-section area of the part. In Brazil, Brazilian Association of Technical Standardization (ABNT) has not yet published a specific AM regulation. ASTM D790, for example, refers to mechanical bending tests of polymers whose workpieces are 100 % filled or dense (Dizon et al., 2018). On the other hand, despite of providing guidance on machine and apparatus configurations, minimum number of tests and approximate external geometry and dimensions of workpieces, ASTM D790 does not establish any criterion regarding the production of the parts (i.e. order or quantity per cycle of printing) or methods of stress analysis for parts with interior not fully filled.

Initial studies of a methodology for determining the ultimate flexural strength (UFS) of printed parts with less than 100 % infill are presented by Rosa et al. (2019) considering the real area moment of inertia (I_{real}).

The objective of this work is to determine the influences of the process parameters (a) percentage (P) of hexagonal (H) infill and (b) quantity of pieces printed per cycle of AM in the flexural mechanical properties of PLA according to Rosa et al. (2019).

2. EXPRIMENTAL SETUP

Workpieces were modeled in SolidWorks® 2018 with dimensions of 127.0 mm length, 12.7 mm width and 3.2 mm thickness according to ASTM D790-17 for three-point bending test. The STL 3D model was exported to the Cliever Studio® software to be converted to CL format, which is a specific Cliever® 3D printer extension. In order to avoid thermal, physical or chemical influences of the raw PLA prior to the AM, two rolls of 1 kg PLA filaments each from the same production batch were used, which were sealed and stored together into a dark and dry environment.

The production of five workpieces for each percentage (P) of hexagonal infill (H) was divided into two groups, one with two workpieces and the other with three workpieces. The groups were produced in distinct printing cycles for each selection of process parameters. In this way, it was possible to evaluate the influence of the time between layer depositions on the mechanical properties of the printed parts. The greater the number of WP's and the greater the distance between them on the printing table, the longer the elapsed time between deposited layers.

In this study a three-axis Cartesian CL2 Pro+ polymeric extrusion 3D printer with enclosure, heated table, and blue filaments with 1.75 mm diameter, both supplied by the Brazilian company Cliever®, were used. The mechanical properties of the Cliever® blue PLA were not provided by the manufacturer. The choice of the blue color is due to the characteristics of the material that favor its observation in optical microscope compared to all the other tested colors.

The bending tests were performed on the MTS Landmark® 647 universal test machine with feed rate of 1.3653 mm/min and 51 mm between clamp supports, in accordance with ASTM D790-17. The tests had the same methodology proposed by Rosa et al. (2019)

The method for determining the real area moment of inertia in relation to the neutral line (I_{real}) [m^4] adopted for calculating the UFS due to variation of infill percentage used in this research was described by Rosa et al. (2019).

The infill percentage of the parts in this study was set before each cycle of manufacturing in a way that give the parts different internal characteristics. This difference is associated with geometrical aspects and also with the time used to build the part. Then, the increase of infill percentage will lead the increase of manufacturing time. This change can also lead in a difference between the mechanical and chemical interactions of the layers related to temperature distribution. This fact is associated of a longer trajectory of the nozzle during each layer. Fig. 2 shows the evolution of infill percentage for hexagonal pattern from 0 % to 30 %. For each value chosen, the internal material volume is different leading to differences in mechanical behavior.

PH 00 PH 10 PH 20 PH 30

Figure 2. Infill percentage of hexagonal raster in extruded blue PLA.

After 3D printing process, the workpieces were packed into PVC hermetically sealed bags and stored in dark and dry environment. This is to minimize absorption of moisture and the influence of UV light over the parts. The workpieces were only removed from their package during dimension measurements and bending tests. The tested parts were submitted to the bending tests with the same life time after printing and were always handled with talc-free nitrile gloves.

2.1 PLA extrusion parametrs

The 3D printing parameters are presented in Tab. 2. These parameters were defined for evaluating the influence of the (a) percentage (P) of hexagonal infill (H) and (b) quantity of printed parts per cycle of AM in the flexural mechanical properties. The parameters of the extrusion process were selected according to literature review, research group experience, and to the 3D printer limitations.

Table 2. Additive manufacturing process parameters for extruded PLA.

Variable Parameters	Infill percentage (P)	0 %; 10 %; 20 %; 30 %
Fixed Parameters	Nozzle diameter	0.35 mm
	Raster strategy	Hexagonal (H)
	Build orientation	Flat
	Infill orientation	45°
	Quantity of perimeter layers	2
	Quantity of bottom and top layers	2 and 2
	Extrusion temperature	185 °C
	Table temperature (first and other layers)	40 °C and 50 °C
	Layer thickness	0.19 mm
	Distance between workpieces during printing process	3.0 mm
	Filament color	Blue Cliever®
	3D printer	Cliever CL2 Pro+®

The aim is to provide light and mechanically resistant workpieces without critical defects, such as: delamination, lack of material, distortion, and out of dimensional tolerance, which could negatively influence the three-point bending tests.

3. RESULTS AND DISCUSSION

Results of UFS and elastic modulus (E) in relation to hexagonal infill and number of parts per printing cycle are presented in Fig. 3. Different values of E found for the same material indicate the influence of the hexagonal shape and the infill percentage in the bending tests. The infill variation acts directly on the cross-sectional area. The bar chart for the E (right) and UFS (left) for percentages (P = 0 %, 10 %, 20 %, 30 %) of hexagonal infill (H) grouped for AM of two and three WP's per cycle are shown in Fig. 3.

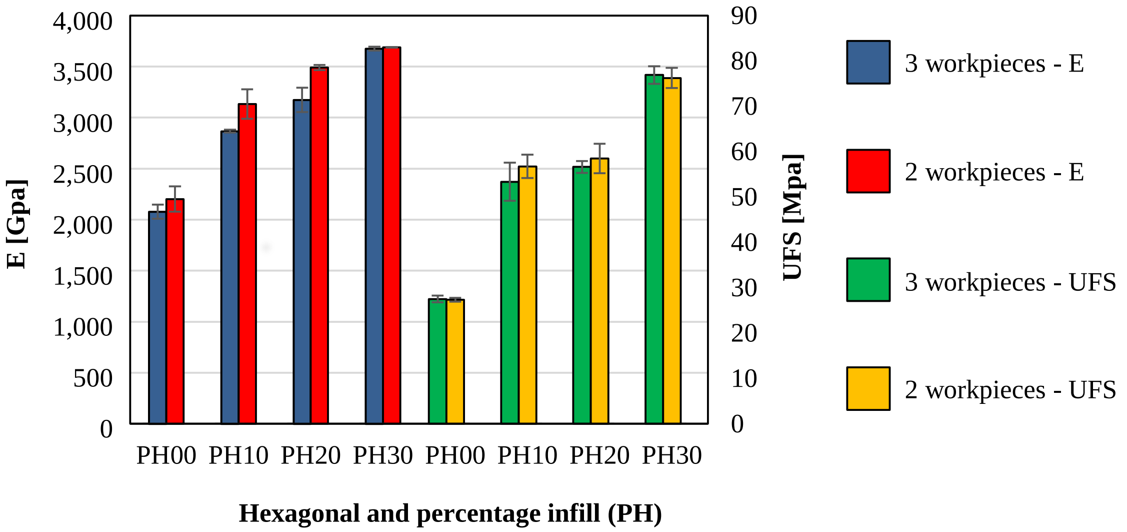

Figure 3. Elastic modulus (E) and ultimate flexural strength (UFS) per group of two and three printed parts per AM cycle on Cliever's blue PLA as a function of infill percentage (P) and hexagonal raster (H).

The highest values of mechanical strength were found for 30 % infill. The workpieces with 30 % infill did not show significant modification of E on the group divisions. The infill percentages of 0 %, 10 %, and 20 % , on the other hand, promoted different mechanical properties in relation to the groups of three and two workpieces, mainly in the intermediate percentages. Thus, the results suggest that the shorter deposition time of the layers acts favorably for the increase of the mechanical properties. This difference can be explained by the fact that the PLA printed in smaller batches presents a shorter manufacturing time, thus preventing the material from having more time to absorb moisture from the environment that could compromises its properties. According to Oever (2010), PLA is hygroscopic. Another explanation for the improvement in UFS and E may be associated to the lower temperature gradient per deposited layer for the smaller groups. The higher temperature of the layer that is receiving the extruded PLA may have improved bonding/adhesion between layers, providing increased strength.

4. CONCLUSION

The increase of infill percentage leads to the higher manufacturing time, but also improved the mechanical properties. The fabrication of more than one workpiece per AM cycle modifies the mechanical properties. *UFS* shows an apparent increase with smaller groups of workpieces per cycle for 10 % and 20 % infill percentages. The change on the number of workpieces per AM cycle changes the printing time between one layer and the next one. Thus, smaller groups have lower temperature gradient between one layer and the next one. This fact is associated of a longer trajectory of the nozzle during each layer. The need for detailed standardization for parts made by AM is therefore necessary due to process parameters influence the mechanical strength.

Future specific technical standards for mechanical testing of parts produced by AM must take into account the geometry and cross-sectional area of parts with infill percentage of less than 100% as well as the number of parts printed per cycle.

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6. RESPONSIBILITY NOTICE

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