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ROBOTIC ADDITIVE MANUFACTURING SYSTEM: STUDY OF THE INFLUENCE OF MOTION PARAMETERS ON THE MECHANICAL PROPERTIES OF 3D- PRINTED TENSILE SPECIMENS

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Abstract. *Additive manufacturing AM in the current scenario is performed using traditional printers, which sit on a flat platform with 3 degrees of freedom which limits the movement of the machine. In this project, a 6 GDL robotic manipulator was used to move a polymer extruder, which provided greater reach in the pallet printing trajectory, using* polylactic acid (PLA) *as raw material with the fused deposition method (FDM). In addition, AM has great economic relevance because in relation to traditional manufacturing it has a higher production volume together with low cost due to the lack of material waste, in relation to the production of parts with high geometric complexity, thus making it possible to have several areas of application. Therefore, the main objective of this article is to study some effects that are related to the trajectory of the manipulator at the time of printing, in order to increase the advancement of this technology and reduce losses that exist in the manufacturing process due to the poor quality of the parts generated by errors that occur along the trajectory of the manipulator, in this study the methodology employed was the variation of speed and density with linear layer filling pattern defined through the Ultimaker Cura Software, to use Cura it was necessary to develop a CAD drawing, through Inventor and thus with G-code generated by Cura transform into machine code using RoboDK software. The print quality of the printed TS's in relation to the virtual model (CAD) was varied, but none of the TS's reached exactly the dimensions projected in the software, a pattern was established where independent of the density of the TS the lower the speed the greater the values of dimension and weight of the TS's.*

Keywords: *additive manufacturing, robotic manipulator, mechanical properties.*

1. INTRODUCTION

The additive manufacturing (AM) in the current scenario of the world is responsible for the manufacture of parts in several areas, such as health with the development and printing of prostheses, in the construction area, in mechanical engineering with the replacement of traditional parts by parts made from 3D printing enabling much more complex geometries, in aerospace, and for domestic use including common people (Gao et al., 2015). In addition,with additive manufacturing it is much easier to produce parts with high complexity, because the 3D printing process with the polymeric extruder attached to the arm of a manipulator allows a movement with more degrees of freedom, its 6 degrees of freedom allows this increase in the movement of the manipulator in time for the manufacture of parts making it more able to reach points where the extruder on a plane can not, such movement is not common and not usual in this type of application in relation to other manufacturing processes. Besides all these points, one still have the increase in production and the low cost in relation to traditional manufacturing processes, which provides an economic gain. The use of robotic manipulators with polymeric extruder attached to the arm for 3D printing is not very common, the idea of this project with the use of robotic manipulator is to gain more degrees of freedom in the printing path, in total 6 degrees of freedom, in order to achieve better results in printing (Bin Ishk, et al., 2016).

In AM there are several parameters that are directly linked to the final quality of the part, some of them related to the extruder such as printing speed, layer thickness, nozzle temperature and temperature in the external environment, the type of material that will be melted among others (Liu, et al., 2017). The effects of these should be studied in order to optimize geometrical, physical and chemical characteristics related to the parts manufactured from AM. Moreover, there are still settings that are linked to the robotic manipulator that are also important, related to the trajectory of the arm along the printing, encompassing the speed and acceleration of the manipulator in the change of direction, if these variables are not well sized can bring major problems in the final results of the printing, causing, for example, economic loss by the loss of material.

The mechanical performance of the parts in tensile strength, compression, stiffness and ductility as well as the surface quality which is related to the production cost since the surface quality depends on the printing time and the time is related to the production cost are properties that are linked one to one and the optimal choice of the combination of factors such as part orientation, layer thickness, density and filling pattern is critical for good final mechanical performance in the parts as well as a decrease in the production cost (Chacón, et al., 2017).

In the current scenario, the AM is performed through traditional printers, which stand on a flat platform with a movement in three directions x, y and z which limits the movement of the machine. In the present article, a 6 axis robotic manipulator will be used to move a small polymer extruder, which gives more flexibility in moving the printing nozzle. Furthermore, the source of raw material that is usually used in additive manufacturing machines is in the form of filaments, and in the present study will be used as feed polymers in the form of pellets, specifically polylactic acid (PLA) .

Within rapid prototyping there are several printing methods, however the one that has been most used is the fused deposition modeling (FDM), this technology has as a feature the application of thermoplastic layer by layer from a platform in three dimensions and this allows the printing of parts with the most complex geometry. In addition, FDM is a technology much easier and cheaper to implement than other printing methods making adhesion easier.(Sa'ude, et al., 2015).

Therefore, taking into consideration all the points that have been cited above and the impacts that the improvements of these parameters can generate to contribute to the development of (AM) within society, this work has as its main objective to study some of the effects that are related to the trajectory of the robotic handler at the time of printing, density and speed of printing will be varied among themselves in order to further increase the advancement of this technology and reduce the losses that still exist in the manufacturing process because of poor mechanical and surface quality of the parts caused by errors that occur along the trajectory of the robotic handler.

2. LITERATURE REVIEW

The importance of Additive Manufacturing (AM) is related to social, environmental, and economic factors, so we must always develop research on issues involving the development of AM to further increase its reach and make it increasingly widespread.

The development of AM using robotic manipulators, is not a trivial technology nowadays. The use of this technique provides increased geometric freedom regarding the parts that will be manufactured, in combination with Fused Deposition Modelling (FDM). However, there are parameters during the steps of this process that can directly affect the final quality of the components, so there are a number of precautions that must be taken to prevent these parameters from affecting the results.

The resistance analysis of the materials produced from the AM made in general by polymers, in this study PLA pellets will be used as raw material for the production of the specimen, are relevant factors within the final results because they are also responsible for affecting the final quality of the component, and may generate a decrease in market interest in these components because of possible imperfections regarding the properties or strengths of the developed components in relation to conventional manufacturing methods.

2.1 Additive Manufacturing

According to Volpato (2017), AM can be defined as a manufacturing process by successive addition of material in the form of layers that are superimposed, the physical part is generated by stacking the sequences of layers. AM has developed enormous potential in the manufacturing process of high geometric complexity, by transforming a complex 3D geometry into a sequence of simpler 2D geometries. However, it is still considered slow compared to traditional manufacturing processes with respect to the volume of parts manufactured.

Increasingly the field of application of AM has been expanding, consequently the processes also develop, generating improvement in the quality of components, new materials and functionality. The expansion of AM reaches the domestic population in the areas of confectionery and leisure with the production of toys.

In the article of Liu et al. (2017) parameters that affect the final quality of the part and the structure of the extruder were investigated. These parameters are linked with print quality, such as material properties, printer temperature, machine melt flow, print speed and layer thickness among others. With this, the authors developed an equation that corresponds to the precision control of the filament width, which depends on some of the parameters mentioned, with the help of the equation it is possible to obtain better results regarding the decrease of the effects of these parameters. In this article it was proven the feasibility of large-sized parts materials using 3D printing by the FDM method, because production by this FDM method reduces expenses and increases the printing speed compared to other processes.

Shah et al. (2019) aims to study large-scale AM with extrusion of fused filament fabrication (FFF) material. This method has some advantages over other manufacturing processes such as low cost, flexible geometry among others. In addition, there is a software behind the printing, which is controlled by G-code, so it is possible to control the printing speed, layer thickness, solid volume and others. The control of these parameters is fundamental to obtain a better print result, with more resolution. Thus, the printing time is closely linked to the quality of the part, or resolution, the longer the printing time, the thinner layers will be made and the better the resolution of the part will be. One of the major challenges present in this study, is the melting of material during printing with larger nozzle sizes without changing the final part. In addition, it was found that large scale printing is difficult to achieve because of the difficulty of controlling parameters at the time of printing.

According to Sanchez (2020) motivated by low recycling rates in the global industry, AM comes with the goal of transforming the linear economy into a circular economy (CE). Therefore, the recovery and preparation steps need further study and therefore proposals involving micro, table and macro levels have been proposed, to validate the Distributed Recycling via Additive Manufacturing (DRAM) it is necessary to prove that there is utilization of the recycled parts.

Conducted by Mishra et al (2021), tests on specimens fabricated from fused deposition modeling (FDM) using polylactic acid (PLA) were subjected to tensile and impact loading to measure the relationship of specimen density and fill pattern to strength.

It is concluded that the delamination of the layers of the mesostructure breaks the crack propagation during the impact, this break in the fracture region gradually increases the energy absorption capacity of the structure.

Studies by Johnson and French (2018) found the importance of strength testing for those producing load-bearing components with consumer-grade 3D printers. Three samples of each material were subjected to the test, if one of them exhibited any structural defects it was reprinted. The tensile yield strength of the samples was directly affected by the fill rate of the part. By using gradually increasing fill rates it was shown that the modulus of elasticity as well as the failure mode of the part (brittle or ductile) were modified

Therefore, it is concluded that as the percentage of filler decreased, it had a significant impact on the tensile strength, and the modulus of elasticity, elongation and failure mode were also affected by the percentage of filler.

According to Dudescu (2017), the article aims to analyze components produced from FDM, it is a layered manufacturing that allows the production of parts with complex geometry, due to the way it is built, layer upon layer, this study will use ABS as raw material for the test specimens (TSs). Parameters such as fill rate, fill patterns and raster orientation were recombined and their results were analyzed in relation to the mechanical tests of tension, compression, bending and impact.

Thus, it was found that TS made from ABS are influenced not only by the infill rate, but also by the filler pattern and its orientation. In addition, the apparent modulus of elasticity increases with the percentage of filler, the higher the filler ratio, the smaller the increase.

With study conducted by Sa'ude (2015), using fused deposition method (FDM), with ABS to ascertain the influence of melt flow index (MFI) and the density of a recyclable ABS material. With four ABS samples, such as ABS filament, expired filament, pellets and part of toys as raw material the study performed tests on these samples.

Therefore, it was noted that the increase in temperature decreased the area in the nozzle zone that conducts the material and thus hinders the formation of the part, when the working temperature fell in the nozzle zone this generates a non-uniform melting and gave rise to buckling during the manufacturing of the filament. Furthermore, the best values found regarding density were for recycled ABS, the other types of materials such as filament showed brittle behavior and the flow of material is not smooth during the manufacturing process when higher temperatures were used.

Studies conducted by Chacón et al. (2017) focused on fabricating PLA structure using fused deposition modeling (FDM), the mechanical behavior of these structures was tested and compared to analyze what effects that printing parameter of orientation, layer thickness, density and fill pattern, feed rate, among others will have on the final quality of the part. The direction of the part construction and the layer thickness in combination with the feed rate were the parameters chosen to be varied. And the final part will be subjected to three-way tensile and flexural testing.

Therefore, according to the obtained results, the construction orientation on-edge showed good mechanical performance in terms of strength, stiffness and ductility, for the layer thickness parameter, in general, the increase of layer implies the decrease of ductility. For the feed rate, as well as, the layer thickness, ductility decreases as the layer thickness increases.

In agreement with Tanveer, Haleem, Suhaib. (2019), on the effect of variable fill density parameter on the mechanical behavior of PLA prints using FDM as thermoplastic extrusion technology and the fabricated TS's were subjected to tensile and flexural tests to obtain values for comparison. For the study thirty-six TS's were printed varying the density percentage at 100%, 75% and 50%.

Consequently, it was understood that the tensile strength is directly proportional to the weight that depends on the density of the filler, which implies that denser parts on the outside provide greater resistance to crack propagation, while the filler with a spread density provides greater flexibility, which increases the tensile strength in the TS. With respect to impact, the inner section should be denser since it achieved better results.

As per Casavola et al. (2019) in studies on orthotropic mechanical properties using (FDM) using classical laminate theory (CLT) as a basis, several advantages of 3D printing over some traditional manufacturing methods have been highlighted. The anisotropic properties of materials have been analyzed as they directly affect the results of the parts, in how they respond under a certain direction. Within the results extracted from the tests we have that the compressive strength is higher for TS's that are axial than transverse with respect to the printing orientation. TS's were tested with a symmetrical and balanced 0, 45° and 90° print angle. Using CLT, it was found that PLA samples are stronger than ABS samples and can break at loads greater than 1000N. In addition, it was noted that PLA is stronger than ABS, however it exhibited a more brittle behavior, it has a greater ability to withstand temperatures higher than ambient.

It was understood from the results that PLA has modulus of rigidity and UTS values that are up to twice those of ABS, and the results suggest that ABS has a more pronounced orthotropic behavior than PLA.

2.2 Using a robotic manipulator for additive manufacturing

According to Ishak, Fisher, Larochelle. (2016), although FDM is quite common in the AM, the application of it on the platform of a robotic arm is nothing trivial and can bring more resources and help improve the final quality of the parts. This happens because the robot has 6 degrees of freedom providing greater mobility along the trajectory of 3D printing. Moreover, other programming techniques are used to control the printer parameters, such as position, speed and pulse, bringing more quality to the final result.

According to Wang et al. (2016) cast pellet molding is a method that uses grain, but allows the mixing of other materials. The work explores the use of a mini extruder attached to a robotic manipulator, which provides higher speed in printing and improved quality of the result, being more flexible as it has 6 GDL and faster than other AM technologies due to the screw inside it.

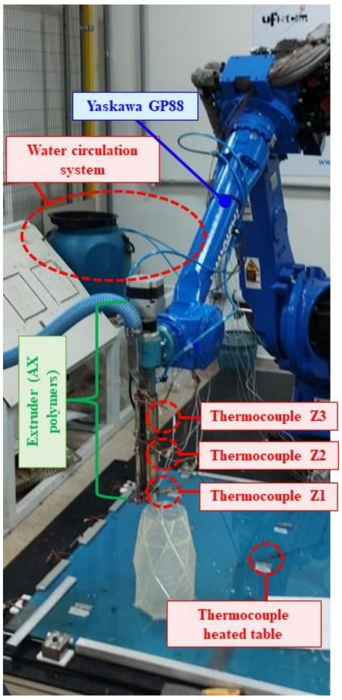
It is concluded that the process brings some advantages such as high production scale due to the extrusion speed and more flexibility in the part geometry due to the use of the industrial robot. However, there are still some disadvantages such as the void in the final result depending on the pressure that will be applied in the extrusion process of the material.

For Ishak, Fisher, Larochelle. (2016), using robotic arms in rapid prototyping has advantages like printing complex geometries due to the additional number of degrees of freedom of the motion. FDM is widely used as it is cheaper and more widespread among all. To achieve good quality printing there are factors such as printing speed, flow rate, layer thickness, orientation, among others that are directly related to the final result of the part, so they need to be properly studied. By means of 3D design, slicing and machine software it was possible to configure all the desired parameters on the part.

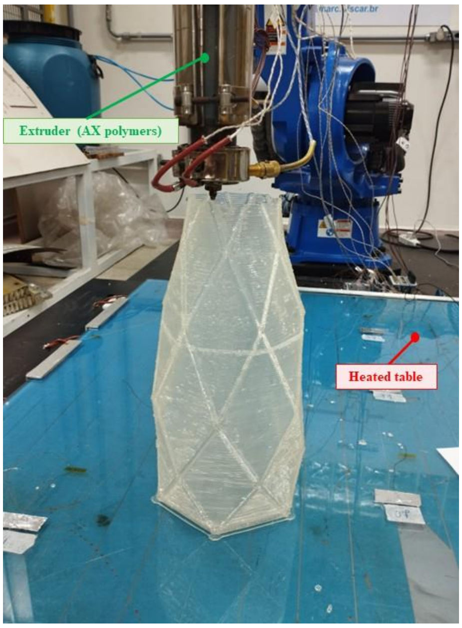
Therefore, it was observed that the integration between the robotic arm and a conventional 3D extruder allowed for multi-plane movement, and this increased the ability to print parts with complex geometry. In the present research, this combination is explored for 3D printing.

3. METHODOLOGY

The goal of the current research is to investigate effects of parameters of the 3D printing process in a robotic AM placell (RAMC). The project that is under development consists of using an Yaskawa GP88 robotic manipulator with a load capacity of 88 kg and 6 axes of motion to move a single-screw extruder provided by the company AX Polímeros (rotation up to about 60 RPM) fed by polymer pellets. The RAMC has a heating table composed of three heating plates with a power of 2kW. In addition, the system contains a water circulation system composed of a pump and a 50 L tank for cooling the extruder in the feeding area of the machine. The system has 4 K-type thermocouples allocated in the 3 heating zones of the extruder and on the heated table respectively. These sensors are used as the basis for controlling the temperatures in these regions from an ON/OFF control made from the TC4S controllers (Autonics). Pictures with the main components of the AM cell are illustrated in Figure 1.



(a) System overview



(b) Detail of the extruder and machine and table Temperature sensors.

Figure 1 – Schematic drawing and photo of the experimental bench to be tested.

The manufacturing cell was used to fabricate test specimens (TS) generated according to ASTM D638 standard for mechanical testing of plastic materials. Type I ASTM D638 was used. Figure 2 shows the ts conforming to the standard dimensions, which are LO = 165 mm, D = 115 mm, L = 57 mm, G = 50 mm, W = 13 mm, WO = 29 mm, and R = 76 mm.

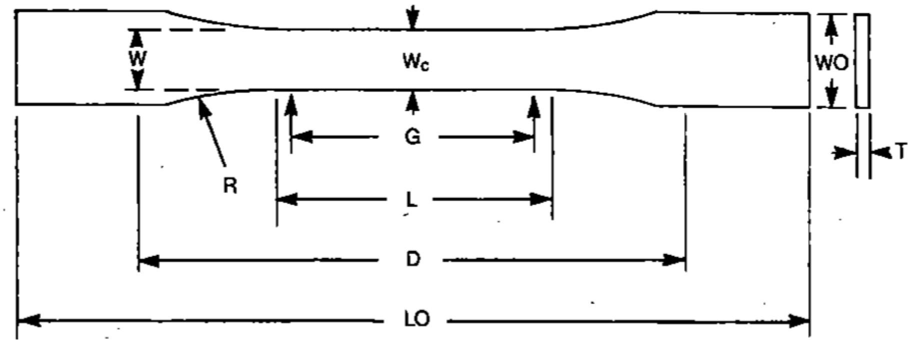
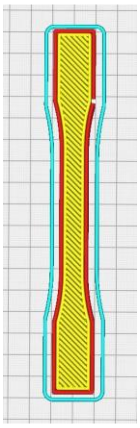
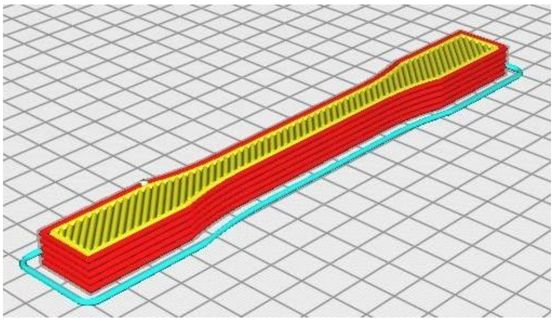


Figure 2 - Specimen for tensile test according to ASTM D638 (ASTM D638, 2002)

The article had a special focus on parameters related to the motion of the robotic manipulator used in this research. With this, the RAMC was fed with PLA pellets, the extruder was set up with fixed temperature of 100°C and screw rotation of 50 RPM. The movement speed of the robot will be varied in three levels: 10, 15 and 20 mm/s, as well as the fill rate was set to: 30, 50 e 70%. The filling pattern of the print layers was set using the Ultimaker Cura (4.13.1) slicing software, in which it was also possible to adjust all the parameters mentioned, as well as the linear pattern. To perform the slicing illustrated in figure 3, through Cura it was necessary to generate a CAD using the Inventor software, figure 4 illustrates what was obtained. When slicing is generated along with the G-Code, the software RoboDK was employed to transform the G-Code generated by Cura into machine code and to be able to make the implementation of the parameters and movements in the robotic manipulator.

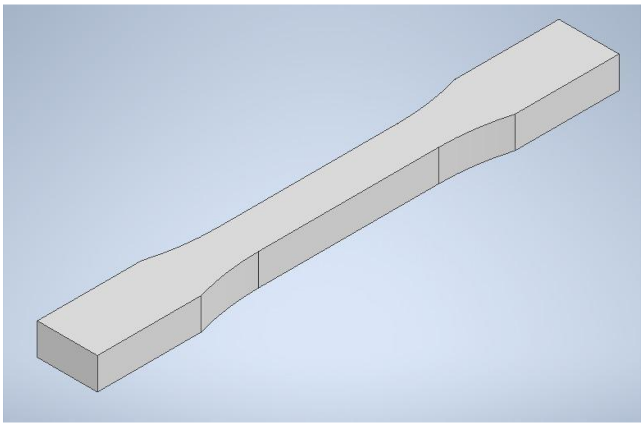


a) Slicing top view

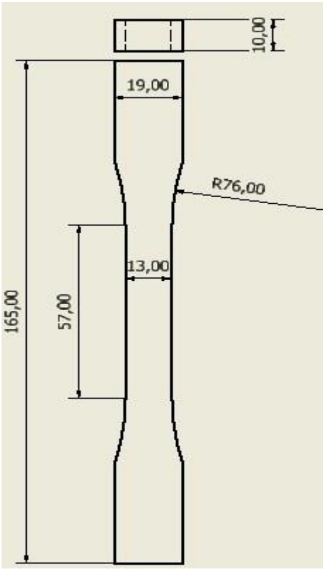


b) Isometric view

Figure 3 - CAD slicing using Ultimaker Cura software (Authors, 2023)



a) Isometric view of the TS



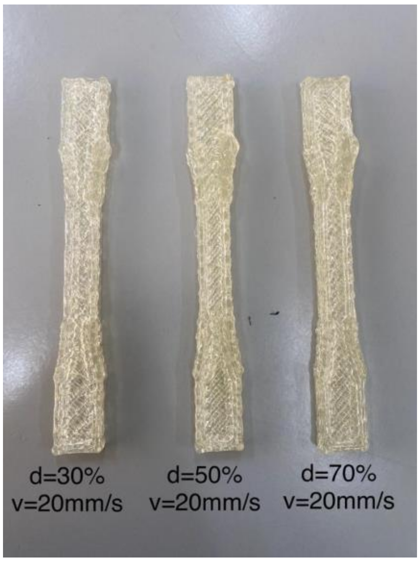
b) Dimensions of the TS

Figure 4 – TS CAD. (Authors, 2023)

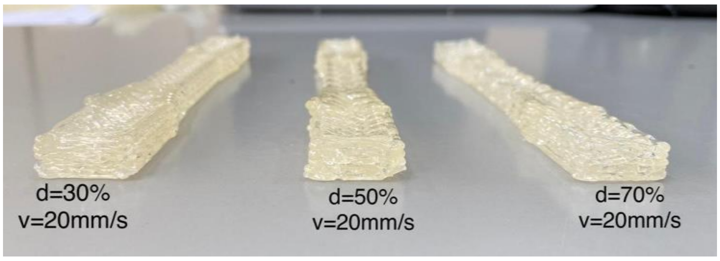
4. RESULTS

The results found in the project so far are in relation to the printing quality of the TS in relation to what was designed by CAD, since those that were fabricated with an infill density of 30%, for example, could present some voids in the structure. Despite this problem, which was already foreseen before printing, all the TS were printed with a certain level of quality, since they solidified and the structure could be subjected to future tensile tests to compare the mechanical strength between all TS. In addition to being printed, all TS's were measured and weighted, as density and area characteristics are extremely relevant when mechanical strength is being analyzed.

Figure 5 shows the results of the TS's ready from the CAD software elaborated and all the processes involved for the final result mentioned above.



a) Top view of the TS's



b) Front view of the TS's

Figure 5 -Final result of the printing of the test specimens (TS).

With this, it was possible to compare the virtual model illustrated in figure 4 with reference in the dimensions shown in figure 2, with the 3D printed TS. Table 1 shows all the measurements of dimensions and masses of all the TS and their respective variations that can be compared with the reference used in the project.

Table 1 - Average of actual values of weight and size of TS's. (Authors, 2023)

Infill density	Velocity (mm/s)	Mass (kg)	Width (mm)	Thickness (mm)
30	10	$0.037^{(*)} \pm 0.001^{(**)}$	$17.48^{(*)} \pm 0.0551^{(**)}$	$10.36^{(*)} \pm 0.050^{(**)}$
30	15	$0.028^{(*)} \pm 0.001^{(**)}$	$14.98^{(*)} \pm 0.347^{(**)}$	$9.62^{(*)} \pm 0.291^{(**)}$
30	20	$0.024^{(*)} \pm 0.001^{(**)}$	$14.52^{(*)} \pm 0.210^{(**)}$	$9.2^{(*)} \pm 0.142^{(**)}$
50	10	$0.043^{(*)} \pm 0.001^{(**)}$	$18.58^{(*)} \pm 0.474^{(**)}$	$11.94^{(*)} \pm 0.594^{(**)}$
50	15	$0.032^{(*)} \pm 0.001^{(**)}$	$17.32^{(*)} \pm 0.476^{(**)}$	$9.20^{(*)} \pm 0.636^{(**)}$
50	20	$0.028^{(*)} \pm 0.001^{(**)}$	$15.38^{(*)} \pm 0.153^{(**)}$	$8.7^{(*)} \pm 0.162^{(**)}$
70	10	$0.048^{(*)} \pm 0.001^{(**)}$	$18.9^{(*)} \pm 0.818^{(**)}$	$13.64^{(*)} \pm 0.247^{(**)}$
70	15	$0.036^{(*)} \pm 0.001^{(**)}$	$16.48^{(*)} \pm 0.461^{(**)}$	$10.34^{(*)} \pm 0.441^{(**)}$
70	20	$0.031^{(*)} \pm 0.001^{(**)}$	$15.08^{(*)} \pm 0.318^{(**)}$	$9.32^{(*)} \pm 0.191^{(**)}$

(*) average value
(**) standard deviation

It was possible to verify that there was some variation between the masses, respecting the increase in density of filling between the TS's with regular standard deviation for all cases and with respect to the dimensions of width and thickness of the TS's there was a very varied standard deviation, caused by the variation of the printing speeds between the prints.

5. CONCLUSIONS

In this paper, the effects of trajectory on the additive manufacturing of parts made from a robotic manipulator equipped with a polymer extruder were presented. The use of a robotic manipulator in the project allowed the printing of the TS in the x,y and z planes, thus increasing the degrees of freedom and allowing greater range during the trajectory.

The results obtained visually so far verify that even varying the densities of 30, 50 and 70% a pattern was established in relation to the printing speed, when the speeds are low for example 10 mm/s the TS presented higher values of dimension and weight and this was observed for all densities, as the printing speed increased these same values decreased proportionally. In general none of the prints had exactly the dimensions of the reference values used, this was due to various printing factors that were not possible to control, for example we could have decreased the layer height to have a better surface finish and get closer to the reference values but we did not have an extrusion nozzle with a smaller radius.

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7. RESPONSIBILITY NOTICE

The authors João Fiore Pereira Lovo, Gustavo Barbosa, Rafaela Silva Barbosa and Sidney Shiki Bruce are the only Ones responsible for the printed material included in this work.