COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-XXXX (XXXX is the identification number of the final paper) ROBOTIC ADDITIVE MANUFACTURING SYSTEM: DEVELOPMENT OF MATHEMATICAL MODELING TO PREPARE 3D PRINTING PROCESSES FOR ABS COPOLYMER

Eduardo Costa Pulquerio
Gustavo Franco Barbosa
Sidney Bruce Shiki
Universidade Federal de São Carlos - Rodovia Washington Luís, km 235 - São Carlos - SP – BR - CEP: 13565-905
eduardopulquerio@gmail.com; gustavofb@ufscar.br; bruce@ufscar.br

Abstract: *Additive manufacturing (AM) is a disruptive production technology with enormous potential to replace conventional manufacturing methods. AM has performed a significant role in industrial manufacturing, due to several technological applications that were developed and ongoing projects. That scenario indicates an optimistic perspective to increase the use of AM. AM based on polymer extrusion is known as FFF (Fused Filament Fabrication) and uses prefabricated filaments to print parts. Outspreading the FFF technology, FGF (Fused Granular Fabrication) or FPF (Fused Particle Fabrication) appears as technology in which an industrial extruder is coupled to the printing system so the polymer is fed as granules or powder directly into the extruder feeder simultaneously with printing event. As further advancement of FFF and FGF/FPF processes, this paper uses Robot-aided Additive Manufacturing in which a single-screw extruder was coupled to an anthropomorphic robotic arm for printing samples in ABS copolymer (Acrylonitrile-Butadiene-Styrene copolymer). The most important parameters of the printing process were evaluated (extruder screw rotational speed - w_m; robot translation speed - v_t; and nominal layer height - Δz_{ref}) to ensure regular and constant geometry of the deposited layer. Samples combining variations of w_m (20, 25 and 30 rpm), v_t (15, 20 and 25mm/s) and Δz_{ref} (2mm) were obtained. Each sample is one-layer 200mm long deposited track. After the cooling time, the layer height (hz) and the layer width (wdt) were measured in five regions of the sample, equally spaced, by using a caliper, to generate average values of height (hz_{mean}) and width (wdt_{mean}). The difference between hz_{mean} and Δz_{ref} determines Δz_{diff}. A linear regression analysis has been performed to describe the relationship between the process parameters and Δz_{diff}, hzmean and wdtmean. The obtained mathematical models show how all factors and some interactions between them influence the responses on deposited track layer. The mathematical models are useful to set up combinations of process parameters that provides a null Δz_{diff} (or nearly null), an adequate polymer flow during the extrusion process, and to estimate dimensions (height and width) of the deposited layer for the printing trajectory. Those dimensions are useful as input data in slicing software's for manufacturing complex 3D objects or parts.*

Keywords: *Robotic, Additive Manufacturing, Extrusion, Polymer*

1. INTRODUCTION

Additive manufacturing (AM), also popularly known as 3D printing, is a disruptive manufacturing technology with enormous potential to replace conventional manufacturing methods. This factor can provide different routes in areas as supply chain and product development, including companies that aggregates services in their product offer (Jiang et al., 2017). AM has gained great popularity in the media and among researchers from different fields (Gao et al., 2015).

ASTM recently adopted the nomenclature 'additive manufacturing' to replace the previous term 'Rapid Prototyping' (RP). Very common in several industries, the term RP was widely used in the context of product development to describe technologies for creating models and physical prototypes, based on digital modeling (Gibson et al., 2015), i.e., prototypes for evaluating the aesthetic, geometric and functional aspects of parts or components before significant financial investments in definitive tools for final manufacture and then for commercialization of the product (Pham & Gault, 1998).

AM has performed an important role in industrial manufacturing area, being used in prototyping, manufacturing of molds (Thompson et al., 2016), such as molds for manufacturing by casting process (Tang et al., 2021) and manufacturing of parts in technological applications (Thompson et al., 2016), so allowing customization for a wide spectrum of applications in the automotive industry, aerospace, engineering, biological systems and food supply chains (Gao et al., 2015), components for medical surgeries (Shi et al., 2021), components for medical diagnosis (Alrashoudi et al., 2021) and electronic components (Lanzolla et al., 2022).

AM contributes to the technological advances needed by the industry, which allows design freedom in parts and products (Thompson et al., 2016). Many companies have adopted the concept of additive manufacturing, or have already started projects to use it, to face new challenges in the manufacture of new products or prototypes. These factors indicate an optimistic perspective for future growth in the use of this technology (Tang et al., 2021). It has advantages over other manufacturing technologies, as the geometry of the printed part can be easily created, modified, and shared for manufacturing in various locations, for better convenience for the company or customer (Hu & Qin, 2020).

According to the ASTM F2792-12a standard, AM is defined as a process of joining materials to obtain objects from a digital 3D model, usually from layer deposition (layer addition), unlike the subtractive manufacturing, whose principle is to obtain an object from the removal of unwanted material from a block of raw material (ASTM, 2012). AM has different technologies in which the printed part acquires the desired geometry and properties in a single or multiple process. In the second case, i.e., multi-step AM, the part geometry is obtained in the primary process and the consolidation of properties takes place in a later secondary process (ASTM International, 2021).

This paper uses molded polymers in a single process, specifically the polymer extrusion technology on a substrate (print bed). AM based on polymer extrusion are systems with lower cost and with a lot of flexibility of use, thus, these are factors that contribute to the increase of its use and popularity, even among the non-specialized community (Gao et al., 2015). As disadvantages, the parts printed by this method have a very rough finish have structural defects, for example, porosities and voids, (Pandey et al., 2003) that can compromise the properties of the part (Agarwala et al., 1996).

As a raw material for extrusion-based AM technology, prefabricated polymeric filaments can be used or polymers in granulated or powdered form can be fed directly into an industrial extruder coupled to the printing system (Sun et al., 2021). When prefabricated filaments are used, the process is known as FFF - Fused Filament Fabrication - (Beniak et al., 2022). When polymers (granulated or powdered) are dosed directly into the extruder feed system, the process is known as FGF - Fused Granular Fabrication - (Cheng et al., 2021) or FPF - Fused Particle Fabrication - (Woern & Pearce, 2018). In this paper, the FGF nomenclature was adopted to refer to the printing process used.

The FGF process has advantages over the FFF system. In the first, it is possible to manufacture printed components using a greater variety of polymeric blends, recycled polymers (Reich et al., 2019), and the manufacture of parts with polymer matrix composites (Cheng et al., 2021). The use of an industrial extruder coupled to the printing system enables the development of polymer blends or composites to meet specific properties or characteristics for parts in technological applications.

Despite the benefits of extrusion-based AM, the FFF and FGF processes are limited in terms of printing speed since the observed low deposition speeds limit their use for large-scale production. In this context, the use of an industrial extruder coupled to an anthropomorphic robot emerges as a solution as it allows a material deposition rate in the order of 10 to 20 times higher than in commercial FFF systems (Magnoni et al., 2017). This factor promotes a series of advantages such as: productivity gains; obtaining larger quantities of printed pieces; possibility of improving the repeatability of the manufacturing process (Walia et al., 2021); improvement in the dimensional tolerance of the part (Liu et al., 2021). In addition, the use of anthropomorphic robots with long reach in printing systems enables the modeling of large parts with reduction or elimination of their partitioning, which is a factor pointed out as a goal for modern AM systems by polymer extrusion and a target for future work (Guo & Leu, 2013).

Obtaining large parts with elimination or reduction of their partitioning is a future challenge from the point of view of processing and raw material. For the first challenge, related to processing, increasing the size of the part provides critical challenges due to the longer time required for manufacturing, the greater probability of warping of the part during printing (Wang et al., 2016) and the formation of density of internal voids in the part (Li et al., 2002). According to Wang et al (2016), it is necessary to optimize the extrusion process to minimize these critical problems. The author proposed extrusion with variable pitch and screw geometry with progressive diameter. In addition, Li et al (2002) propose formats for the extrusion die section as a way of controlling the shape of the extruded filament, thus minimizing the density of internal voids in the printed parts. Another aspect of processing large parts concerns the difficulty in dimensional accuracy of the height of the parts as the layers are successively deposited (Rebaioli et al., 2019). The author proposes that real-time correction of the piece slicing be made for dimensional control of the large piece. Regarding the second challenge, referring to raw materials for large parts, it is necessary to develop AM with structural materials (Liu et al., 2021). According to the author, pure polymers as a raw material have limited mechanical strength for functional printed parts, which makes it impossible to develop a broader range of technical part for different industries. To overcome the challenge of better mechanical performance, polymeric matrix composites can be developed with the addition of reinforcements in the form of particles or fibers, including nanomaterials (Yaragalla et al., 2021), and then used in the manufacture of parts by extrusion-based AM. Using several types of reinforcements, polymer matrix composites can achieve a better balance of mechanical, electrical, and thermal properties (Liu et al., 2021). The extrusion-based AM-FGF technology allows the development of blends and composites with properties best suited to meet specific engineering requirements in technological applications. There is then the possibility of using a wider variety of materials in the manufacture of technical parts (Felber et al., 2021). AM with structural composites, based on a polymeric matrix reinforced with fibers and other types of fillers, is a goal in studies of applications that replace metallic parts in market segments such as aeronautics and automobile (İpekçi & Ekici, 2022), and naval (Moreno Nieto et al., 2018).

In summary, manufacturing of parts: faster; with better repeatability of the process; large-sized; with high mechanical strength; and with dimensional accuracy are the main challenges for the future of AM technology based on polymer extrusion.

This experimental work explores additive manufacturing technology via fused granular fabrication with robotic process automation, which deals with a system in which a single screw industrial extruder was coupled to an anthropomorphic robotic arm, designed and developed at the Additive Manufacturing and Automation Research Center (AMARC) of the Department of Mechanical Engineering at the Federal University of São Carlos (DEMec/UFSCar). The objective of this paper is to evaluate and to synchronize the main parameters of the printing process, verifying the effect of those parameters on the geometry of the printed layer. The main parameters of the printing process were adjusted to guarantee the regularity of the deposited layer. The samples format were single-layer rectilinear tracks. In this experimental work, the samples obtained were single-layer rectilinear tracks, which can be interpreted as a single layer deposited on a printing trajectory.

The parameters under study are Extruder screw rotation speed (w_m), Robot translation speed (v_t) and Nominal layer height (Δz_{ref}). Samples combining variations of w_m (20, 25 and 30 rpm), v_t (15, 20 and 25mm/s) and Δz_{ref} (2mm) were obtained. The average height (hz_{mean}) and average width (wdt_{mean}) of the tracks were then measured. The subtraction of Δz_{ref} by hz_{mean} determined the Difference between nominal and measured mean layer height (Δz_{diff}). Mathematical regression analysis was performed to describe the correlation between the process parameters under study versus wdtmean, versus Δzdiff, and versus hzmean to generate regression models for combinations of process parameters. The regression models obtained will be useful in future experimental work to predict the adequate flow of polymer in the manufacturing process, to provide null (or close to null) difference in Δz_{diff}, and to estimate height and width values for the deposited layer. These values are input data for slicing software for manufacturing objects or complex 3D parts.

2. MATERIAIS AND METHODS

2.1 Materials

Extrusion-based additive manufacturing with robotic process automation was used as an improvement to the FFF and FGF/FPF processes. A single-screw industrial extruder, manufactured by the company AX-Plásticos, was coupled to an anthropomorphic robotic arm, manufactured by Yaskawa Motoman, model GP88 (robot with six axes, 88 kg payload, and 2,236 mm of horizontal reach). The extruder derives from the "micro extruders" product family, and it has a pellet feeding system (hopper), three heated zones and a conic deposition nozzle (with a Ø 2 mm hole). The printing cell used is shown in fig. 1.

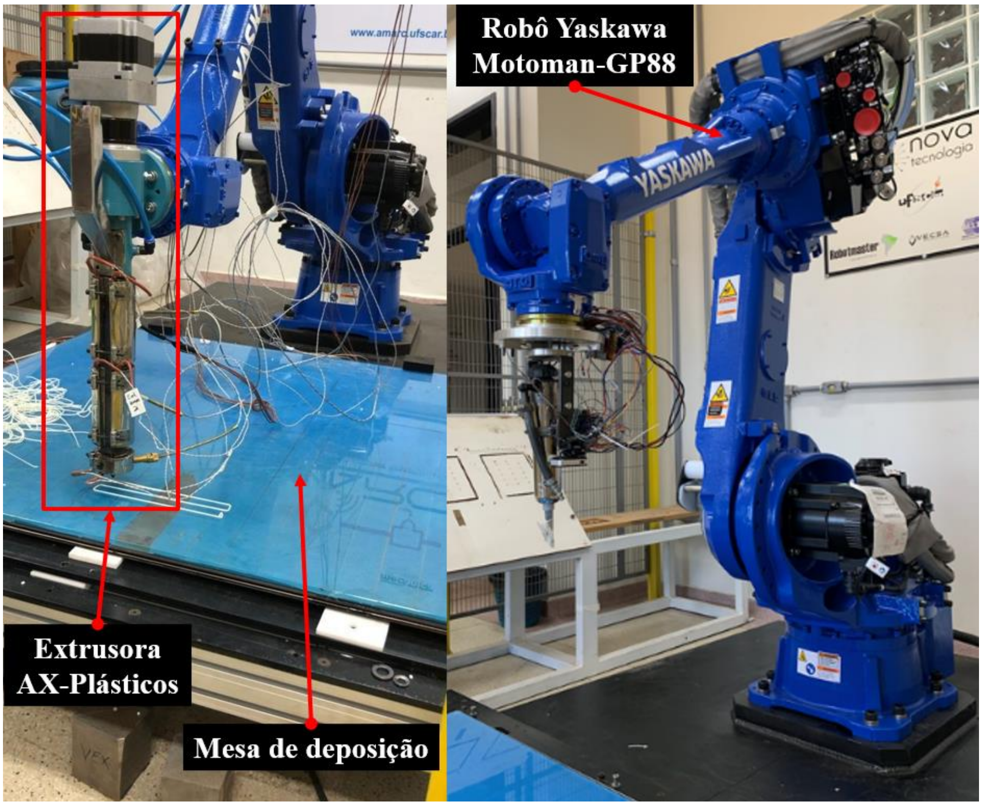

Figure 1 – Additive Manufacturing Cell for Fused Granular Fabrication using robotic process automation

The raw material used in the experiment is ABS copolymer (Acrylonitrile-Butadiene-Styrene copolymer), Cycolac^{TM} brand, grade EX58F, manufactured by SABIC. This material was chosen because ABS copolymers are widely used for printing parts in extrusion-based AM technologies, even in technologies that use filaments.

2.2 Methods and Experimental Design

The steps adopted as methodology in this experimental work are illustrated in fig. 2.

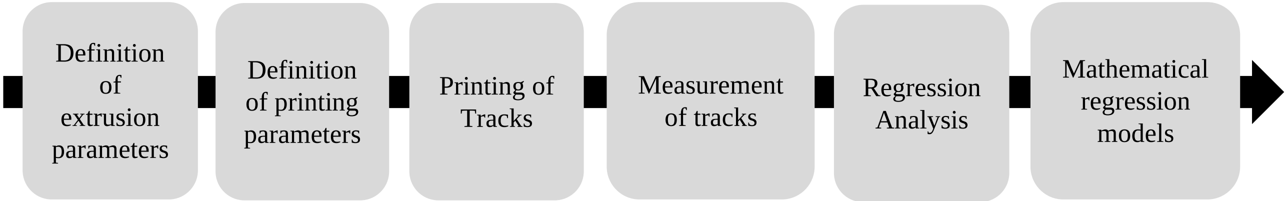

Figure 2 - Flowchart of the steps of the experiment methodology

Process parameters for the polymer extrusion are fixed and are presented in Table 1. Those parameters refer to the dehumidification of the polymer, the temperature of the heating zones of the extruder, and the temperature of the print bed.

Table 1 - Process parameters for the polymer extrusion

Factor	Value	Unit
Dehumidification – Temperature	80	°C
Dehumidification – Time	4	h
Extruder – Temperature Zone 1 (T_1)	200	°C
Extruder – Temperature Zone 2 (T_2)	210	°C
Extruder – Temperature Zone 3 / Nozzle (T_3)	220	°C
Print Bed - Temperature (T_{hb})	80	°C

The main parameters for the printing process were adjusted to guarantee the regularity of the deposited layer. The samples format were single-layer rectilinear tracks. The parameters under study are Extruder screw rotation speed (w_m), Robot translation speed (v_t) and Nominal layer height (Δz_{ref}). Experimental design combining variations of w_m (20, 25 and 30 rpm), v_t (15, 20 and 25mm/s) and Δz_{ref} (2mm) were obtained and presented in table 2. The combination of test possibilities is 3 x 3 = 9 different experimental conditions. When repeated three times, they totaled 27 samples. Every sample is a 200mm long single-layer rectilinear track, which can be interpreted as a single layer deposited on a printing path.

Table 2 – Experimental design for the printing process parameters and samples

Factor	Symbol	Unit	Value
Extruder screw rotation speed	w_m	rpm	20 / 25 / 30
Robot translation speed	v_t	mm/s	15 / 20 / 25
Nominal layer height	Δz_{ref}	mm	2
Track sample length	-	mm	200
Quantity of layers	-	un	1

The processing of molten polymers normally promotes a significant amount of extensional flow (Shenoy, 1999), which impacts the final properties of polymeric feedstock products. Divergent flow is also observed with the expansion of the flow front, into the radial direction, of the extruded polymer at the exit of the extrusion die as a bioriented extensional flow (Shenoy, 1999). This paper deals with the development and synchronization of printing process parameters. It can be noticed that the combination between the robot translation speed and the extruder screw rotation speed can increase or decrease the expansion of the divergent flow, in the radial direction, and the extensional flow, at the exit of the extruder die. This means influence on the final diameters of the deposited layer in the printing process. Thus, Δz_{ref} equal to 2.0 mm was established as an initial reference for process development in the printing system used.

After cooling, the samples height (h_z) and width (wdt) were measured using a Mitutoyo Digimatic CD-8" ASX caliper (with a resolution of 0.01mm). The measurements were taken in five regions of the sample, equally spaced, generating the average of the values, hz_{mean} and wdt_{mean}, respectively. The difference between the nominal fillet height (Δz_{ref}) and the average height (hz_{mean}) was calculated by the equation:

$$\Delta z_{diff} = \Delta z_{ref} - hz_{mean} \quad (1)$$

Track uniformity was analyzed through the ratio between the average height (hz_{mean}) and average width (wdt_{mean}), calculated by the equation:

$$U = \frac{hz_{mean}}{wdt_{mean}}\ x\ 100 \quad (2)$$

After obtaining data correlating the process parameters (w_m, v_t, e Δz_{ref}) versus Δz_{diff}, versus hz_{mean}, and versus wdt_{mean}, a regression analysis was performed to describe the interaction between the variables through a mathematical regression model.

3. RESULTS AND DISCUSSION

Using the process parameters for polymer extrusion (table 1) and applying the combinations of parameters for the printing process (table 2), samples were obtained in the form of 200mm long single-layer rectilinear track, in a single layer deposited on a printing path. The samples are shown in fig. 3.

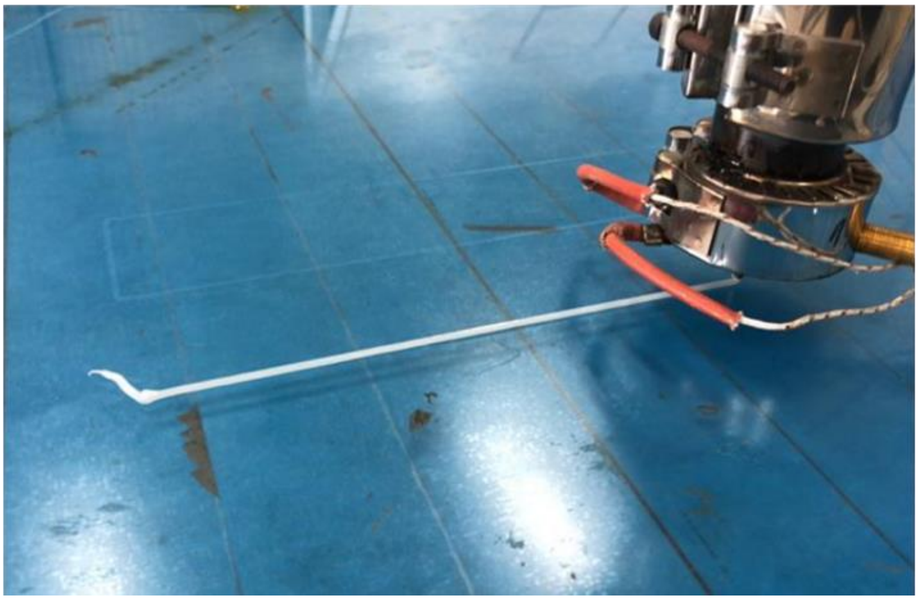

Figure 3 – Single-layer rectilinear track used as sample on this experimental work

After cooling, the samples height (hz) and width (wdt) were measured using a Mitutoyo Digimatic CD-8" ASX caliper (with a resolution of 0.01mm). The measurements were taken in five regions of the sample, equally spaced, generating the average of the values, hz_{mean} and wdt_{mean}, respectively. The difference between the nominal fillet height (Δz_{ref}) and the average height (hz_{mean}) was calculated by the equation (1), resulting in Δz_{diff}. The Track Uniformity (U) was calculated by equation (2).

Uniformity of the deposited layer and stability of the extrusion process

The extrusion system used could produce extruded polymer without interruption in all tests, which demonstrates that the polymer transformation process parameters (tab. 1), together with the screw rotation parameter - w_m - (tab 2) generated sufficient shear rate to melt the ABS copolymer and so generate continuous extrusion. The uniformity of the deposited layer was evaluated through the ratio between h_{mean} and wdt_{mean}. The smaller the difference between these two magnitudes, in the same experimental condition, the more uniform the layer, the cross section of the extruded track being more like a circle. The greater the difference between h_{mean} and wdt_{mean}, the cross section of the extruded track resembles an ellipse. Li et al (2002) proposed a theoretical model to analyze the effect of void density in the deposited printing layers. The ideal condition to minimize the density of voids during printing is the deposition of an extruded layer with a cross section closer to an ellipse (Li et al., 2002), as represented in fig. 4. According to Magnoni et al (2017), more uniform extruded layers, with a cross-section resembling a circle, i. e., like cylindrical tracks simply deposited on the printing table, are harmful from the point of view of part manufacturing. In this concept, experimental conditions 4 (w_m=20 rpm; v_t=20 mm/s; Δz_{ref}=2 mm), 7 (w_m=20 rpm; v_t=25 mm/s; Δz_{ref}=2 mm) and 8 (w_m=25 rpm; v_t=25 mm/s; Δz_{ref}=2 mm)s; showed little variation between hz_{mean} and wdt_{mean} (in the order of 5%, as shown in tab. 3), i. e., similar to uniform cylindrical filaments, that means they are not desirable process conditions.

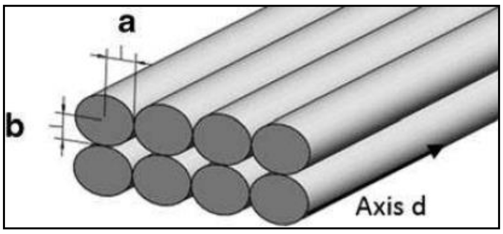

Figure 4. Ideal cross section that minimizes the density of voids in the manufacture of printed parts according to the model proposed by Li et al (2002); 'a' is half the width and 'b' half the height of the deposited filament. Source: Wang et al 2016, p. 42.

Width and Height of the deposited layer

Table 3 presents the results of the effects of the combination of process parameters (w_m, v_t and Δz_{ref}) on the hz_{mean} and wdt_{mean} results of the deposited layer.

Table 3. Experimental results of average height and width, difference between nominal and actual height and sample uniformity with different combinations of process parameters

Experimental Condition	w_m [rpm]	v_t [mm/s]	Δz_{ref} [mm]	hz_{mean} [mm]	Δz_{diff} [mm]	wdt_{mean} [mm]	Track Uniformity (U) [%]
Cond. 1	20	15	2.00	1.79	0.21	1.99	10
Cond. 2	25	15	2.00	2.02	-0.02	2.51	20
Cond. 3	30	15	2.00	1.99	0.01	2.64	25
Cond. 4	20	20	2.00	1.70	0.30	1.78	5
Cond. 5	25	20	2.00	1.81	0.19	1.97	8
Cond. 6	30	20	2.00	1.89	0.11	2.19	14
Cond. 7	20	25	2.00	1.53	0.47	1.61	5
Cond. 8	25	25	2.00	1.72	0.28	1.82	5
Cond. 9	30	25	2.00	1.79	0.21	2.00	10

Figure 5 presents the results graphically, expressing the individual plot of the Δzdiff value.

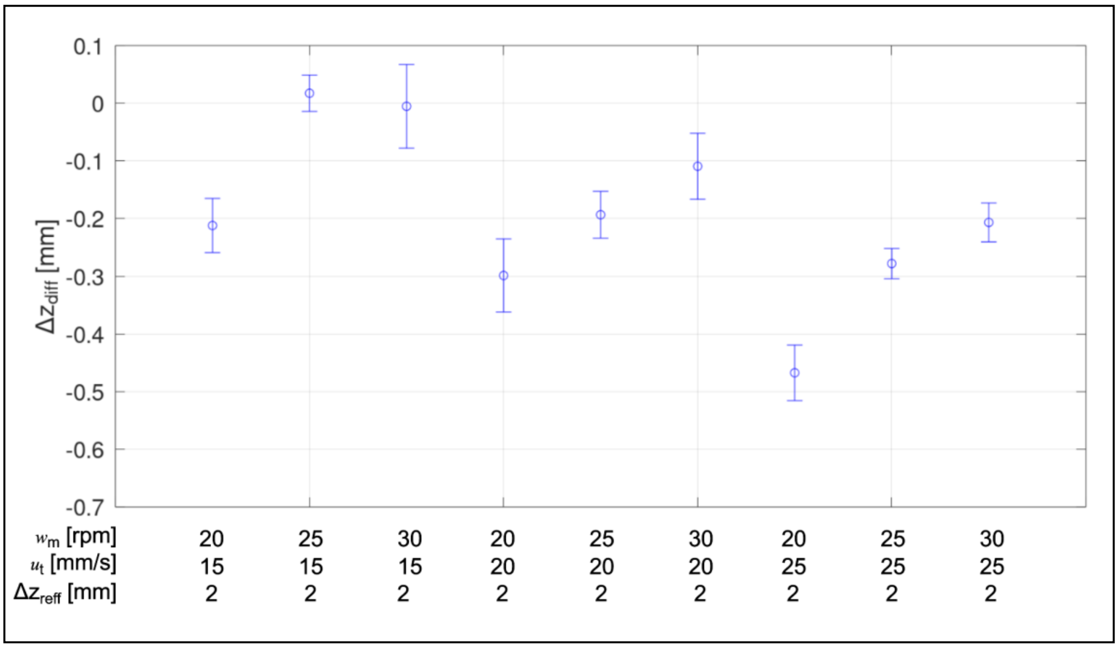

Figure 5. Individual plot of Δz_{diff} value. The circle represents the mean values found, and the bars the standard deviation for each mean value.

Figure 5 demonstrates that the smallest height errors found (Δz_{diff}), i. e., the smallest difference between nominal and obtained height happens at experimental conditions 2, 3 and 6, with Δz_{ref} set to 2mm. In special, the experimental conditions 2 (w_m=25rpm; v_t=15mm/s; e Δz_{ref}=2mm) and 3 (w_m=30rpm; v_t=15mm/s; e Δz_{ref}=2mm) showed Δz_{diff} values close to zero (null), which is desirable from the manufacturing point of view as a way to obtain better dimensional accuracy of printed parts and also a larger contact surface for adhesion of the deposited material. Tests with extruder screw rotation speed even higher than those experienced could confirm the stabilization tendency of null Δz_{diff} (or close to null), however, the motor-reducer assembly in the extruder used did not demonstrate enough torque capacity to work in those conditions. As an option to obtain future results with null Δz_{diff} (or close to null), future tests using Δz_{ref} smaller than 2.00mm for the ABS copolymer should be considered.

Figures 6 and 7 present the graphical results, expressing the individual plot of the value of hz_{mean} and wdt_{mean}, respectively.

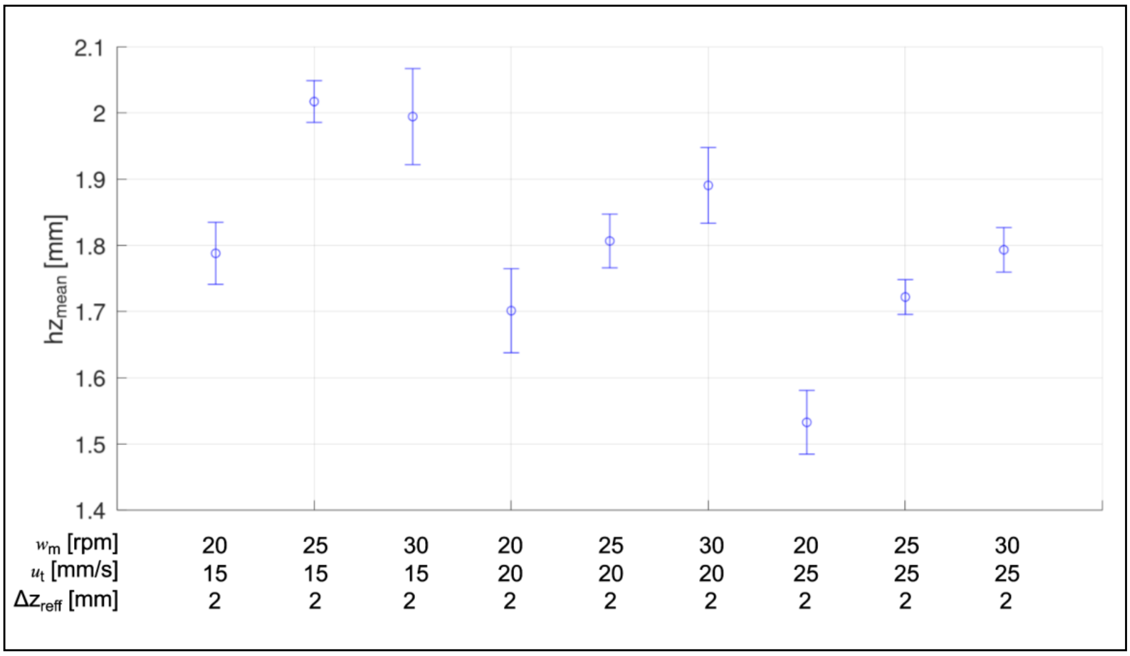

Figure 6. Individual Plot of hz_{mean}. The circle represents the mean values found, and the bars the standard deviation for each mean value.

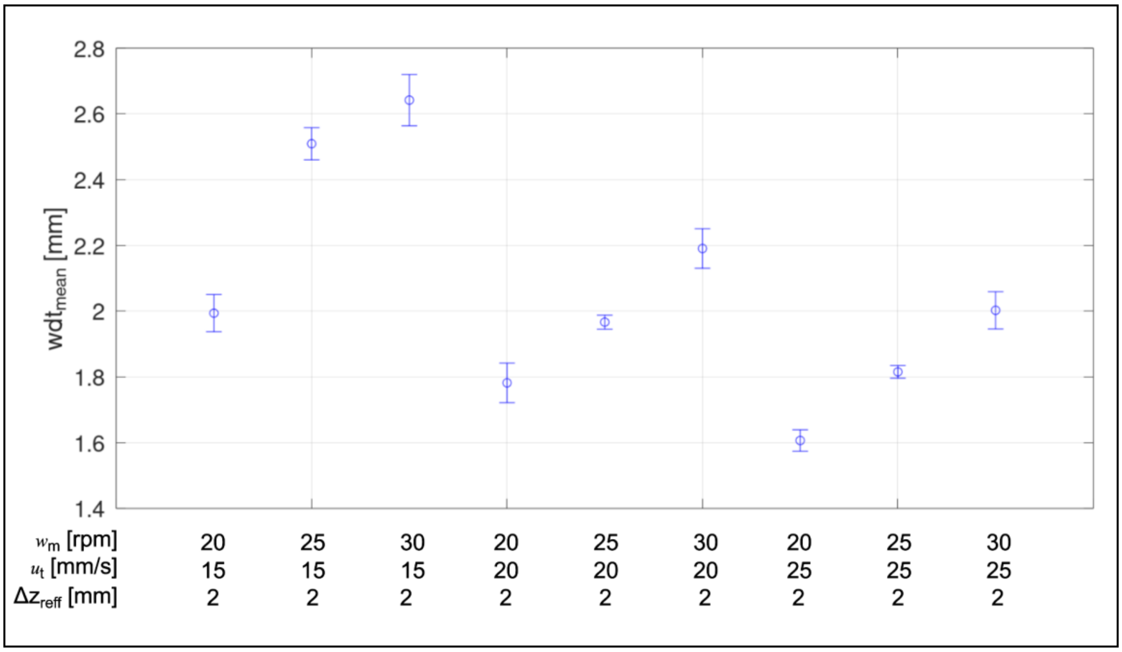

Figure 7. Individual Plot of wdt_{mean}. The circle represents the mean values found, and the bars the standard deviation for each mean value.

Figures 6 and 7 demonstrate that, at the same robot translation speed, the increase of the extruder screw rotation speed represented an increase in the average of height and width of the deposited track, due to the greater amount of polymer available for deposition in the extrusion process. The standard deviation of height and width measurements were low, which demonstrates good stability of the printing system. Figure 6 demonstrates that for robot translation speeds equal to 20 and 25mm/s, at all tested extruder screw rotation speeds, the average height of the track was below the nominal height. For these two speeds, there was a tendency towards an increase in average height with increasing extruder screw rotation speed, however, it is not possible to state that at extruder screw rotations speed higher than those evaluated there would be an equilibrium in average height into nominal height, despite a trend in this direction. In the case of the test with a robot translation speed of 15mm/s and an extruder screw rotation speed of 20rpm, the average height of the track was below the nominal height. For the robot translating at a speed of 15mm/s and the extruder screw rotating at 25 and 30rpm, the average height was close to the nominal height, i.e., with low Δz_{diff}. Tests at extruder screw rotation speeds even higher than those experienced could confirm the tendency of stabilization Δz_{diff} null (or close to null), which would be desirable in the manufacturing process of parts by AM. About the average width of the tracks, shown in figure 7, the increase in the extruder screw rotation speed provided an increase in the width of the track. The width of the track can be understood as a consequence of the selected process parameters.

Difference in layer height and thickness

The results obtained demonstrate that the combination of low extruder screw rotation speed and high robot translation speed resulted in significant differences in Δz_{diff}, which suggests that the volume of extruded polymer was not sufficient to maintain adequate flow por deposition on the print bed. Thus, the experimental condition 7 (w_m =20rpm; v_t =25 mm/s; e Δz_{ref}=2 mm), in addition to providing inadequate deposition, like filament without deformation (circle cross-section), presented Δz_{diff} equal to 0.47 mm, i. e., did not represent a suitable combination of process.

Process conditions 2 (w_m=25 rpm; v_t=15 mm/s; and Δz_{ref}=2 mm), 3 (w_m=30 rpm; v_t=15 mm/s; and Δz_{ref}=2 mm) and 6 (w_m = 30 rpm; v_t=20 mm/s; and Δz_{ref}=2 mm), showed the greatest differences between hz_{mean} and wdt_{mean}, being 20, 25 and 14%, respectively, meaning greater deformation of the deposited material (elliptical cross-section), which suggests better combinations of process parameters from the point of view of manufacturing by extrusion-based AM technology.

Regression analysis

To correlate the relation of the process parameters w_m, v_t and Δz_{ref} with the results-responses in Δz_{diff}, hz_{mean} and wdt_{mean} of the printed tracks, a regression analysis with multiple variables was performed. Those analysis was made by using Microsoft Excel software. The results of the analyzes demonstrated how the process parameters, and how some interactions between the parameters, influenced the responses. The main results of the regression analysis (p-value and estimated standard deviation) are shown in Table 4, while the estimated regression models for the Δz_{diff}, hz_{mean} and wdt_{mean} responses are expressed by equations (3), (4) and (5), respectively. The adequacy of the regression models is demonstrated by the satisfactory coefficients of determination (R^2_{adj}) 84.61%, 84.61% and 92.8%, respectively.

Table 4. Results of regression analysis: p-values and standard error

	Intersection	w_m	v_t	Δz_{ref}	$w_m.v_t$	$w_m.\Delta z_{ref}$	$v_t.\Delta z_{ref}$	w_m^2	v_t^2	**Standard Error [mm]**
Δz_{diff}	1.7×10^{-5}	---	---	---	---	2.4×10^{-10}	3.2×10^{-3}	1.0×10^{-9}	0.3949	0.05
hz_{mean}	0.0756	---	---	---	---	2.4×10^{-10}	3.2×10^{-3}	1.0×10^{-9}	0.3949	0.05
wdt_{mean}	0.0169	---	---	---	---	3.7×10^{-13}	1.9×10^{-12}	8.2×10^{-6}	7.1×10^{-15}	0.07

$$\Delta z_{diff} = 1.4283 + [-0.0005 \times (\omega_m \times \vartheta_t)] + [-0.0708 \times (\omega_m \times \Delta z_{ref})] + [0.0260 \times (\vartheta_t \times \Delta z_{ref})] + (0.0026 \times \omega_m^2) + (-0.0003 \times \vartheta_t^2) \quad (3)$$

$$hz_{mean} = 0.5717 + [0.0005 \times (\omega_m \times \vartheta_t)] + [0.0708 \times (\omega_m \times \Delta z_{ref})] + [-0.0260 \times (\vartheta_t \times \Delta z_{ref})] + (-0.0026 \times \omega_m^2) + (0.0003 \times \vartheta_t^2) \quad (4)$$

$$wdt_{mean} = 1.0210 + [-0.0025 \times (\omega_m \times \vartheta_t)] + [0.1102 \times (\omega_m \times \Delta z_{ref})] + [-0.0894 \times (\vartheta_t \times \Delta z_{ref})] + (-0.0024 \times \omega_m^2) + (0.0046 \times \vartheta_t^2) \quad (5)$$

Process parameters can be selected from the found mathematical regression models. Equation (3) can be used to find combinations of process parameters that guarantees a null (or close to null) height difference (Δz_{diff}), i.e., combinations between the extruder screw rotation speed and the robot translation speed which provide appropriated polymer throughput for the layer height set in the robot motion control. For example, if elevated levels of extruder screw rotation speed and robot translation speed are selected to achieve the highest productivity, Equation (3) provides the suitable value of nominal layer height. As a result of the adjustments made through equation (3), equations (4) and (5) can be used to estimate track height and track width values, respectively, for the selected process parameter combination, which are useful as input data in slicing software for manufacturing objects or complex 3D parts.

4. CONCLUSIONS

Additive Manufacturing is a disruptive fabrication technology with enormous potential to replace conventional manufacturing methods and plays a significant role in the industrial manufacturing of several types of products. The FFF technology uses prefabricated polymeric filaments, while the FGF uses an extruder coupled to the layer printing system. Both FFF and FGF processes have benefits and limitations. They are limited due to low printing speed, which may limit the possibility of large-scale manufacturing. The association of robotics to extrusion-based AM intends to overcome printing speed limitations, allow the modeling of large parts with less or without partitioning, and improve the repeatability of the process.

The main parameters for the printing process were adjusted to guarantee the regularity of the deposited layer. Experimental conditions 4 (w_m=20 rpm; v_t=20 mm/s; Δz_{ref}=2 mm), 7 (w_m=20 rpm; v_t=25 mm/s; Δz_{ref}=2 mm) and 8 (w_m=25 rpm; v_t=25 mm/s; Δz_{ref}=2 mm)s; showed little variation between hz_{mean} and wdt_{mean} (in the order of 5%, as shown in tab. 3), i. e., similar to uniform cylindrical filaments, that means they are not desirable process conditions. Regarding the experimental conditions 2 (w_m=25 rpm; v_t=15 mm/s; e Δz_{ref}=2 mm), 3 (w_m=30 rpm; v_t=15 mm/s; e Δz_{ref}=2 mm) and 6 (w_m=30 rpm; v_t=20 mm/s e Δz_{ref}=2 mm), these are the most appropriate process combinations, as they present greater deformation of the deposited material, with the greatest differences observed between hzmean and wdtmean (20, 25 and 14%, respectively). The accuracy between the nominal height and actual height of the deposited layer (Δz_{diff}) demonstrated that experimental conditions that combined low extruder screw rotation speed with high robot translation speed resulted in significant differences in Δz_{diff}, which suggests that the volume of extruded material was not enough to keep minimum Δz_{diff} (ideal situation). The regression analysis with multiple variables correlated the relation of the process parameters w_m, v_t and Δz_{ref} with the results-responses in Δz_{diff}, hz_{mean} and wdt_{mean} of the printed tracks. The regression analysis provided mathematical models to find combinations of process parameters that provide null (or close to null) difference between the nominal and current real deposited heights (Δzdiff), considering adequate polymer flow during the manufacturing process. As a consequence of process parameters selected by using the regression model of equation (3), the regression models of equations (4) and (5) can be used to estimate values of height and width of the layer that are useful as input data in slicing software for manufacturing of complex 3D objects or parts.

5. ACKNOWLEDGEMENTS

This work was funded by FAPESP under grant number 2019/22115-0 and CAPES under grant number 88882.461700/2019-01.

6. REFERENCES

Agarwala, Mukesh K., Vikram R. Jamalabad, Noshir A. Langrana, Ahmad Safari, Philip J. Whalen, e Stephen C. Danforth. 1996. “Structural quality of parts processed by fused deposition”. *Rapid Prototyping Journal* 2(4):4–19. doi: 10.1108/13552549610732034.

Alrashoudi, Abdulelah A., Hamed I. Albalawi, Ali H. Aldoukhi, Manola Moretti, Panayiotis Bilalis, Malak Abedalthagafi, e Charlotte Hauser. 2021. “Fabrication of a Lateral Flow Assay for Rapid In-Field Detection of COVID-19 Antibodies Using Additive Manufacturing Printing Technolog”. *International Journal of Bioprinting* 7(4):399. doi: 10.18063/ijb.v7i4.399.

ASTM. 2012. *Designation F2792−12a: Standard Terminology for Additive Manufacturing Technologies (Withdrawn 2015)*. West Conshohocken, PA: ASTM International. doi: 10.1520/F2792-12A.

ASTM International. 2021. *Additive Manufacturing, Design, Functionally Graded Additive Manufacturing*. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International.

Beniak, Juraj, L’Ubomír Šooš, Peter Križan, Miloš Matúš, e Vít Ruprich. 2022. “Resistance and Strength of Conductive PLA Processed by FDM Additive Manufacturing”. *Polymers* 14(4). doi: 10.3390/polym14040678.

Cheng, Tiffany, Dylan Wood, Laura Kiesewetter, Eda Özdemir, Karen Antorveza, e Achim Menges. 2021. “Programming material compliance and actuation: Hybrid additive fabrication of biocomposite structures for large-scale self-shaping”. *Bioinspiration and Biomimetics* 16(5). doi: 10.1088/1748-3190/ac10af.

Felber, S. O., M. Aburaia, W. Wöber, e M. Lackner. 2021. *Parameter Optimization for the 3D Print of Thermo-Plastic Pellets with an Industrial Robot*.

Gao, Wei, Yunbo Zhang, Devarajan Ramanujan, Karthik Ramani, Yong Chen, Christopher B. Williams, Charlie C. L. Wang, Yung C. Shin, Song Zhang, e Pablo D. Zavattieri. 2015. “The status, challenges, and future of additive manufacturing in engineering”. *Computer-Aided Design* 69:65–89. doi: 10.1016/j.cad.2015.04.001.

Gibson, Ian, David Rosen, e Brent Stucker. 2015. “Development of Additive Manufacturing Technology”. P. 19–42 em *Additive Manufacturing Technologies*. New York, NY: Springer New York.

Guo, Nannan, e Ming C. Leu. 2013. “Additive manufacturing: technology, applications and research needs”. *Frontiers of Mechanical Engineering* 8(3):215–43. doi: 10.1007/s11465-013-0248-8.

Hu, Chao, e Qing Hua Qin. 2020. “Advances in fused deposition modeling of discontinuous fiber/polymer composites”. *Current Opinion in Solid State and Materials Science* 24(5). doi: 10.1016/j.cossms.2020.100867.

İpekçi, Ahmet, e Bülent Ekici. 2022. “Effect of fiber set-up and density on mechanical behavior of robotic 3D-printed composites”. *Emerging Materials Research* 11(1):160–66. doi: 10.1680/jemmr.21.00120.

Jiang, Ruth, Robin Kleer, e Frank T. Piller. 2017. “Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030”. *Technological Forecasting and Social Change* 117:84–97. doi: 10.1016/j.techfore.2017.01.006.

Lanzolla, A. M. L., F. Attivissimo, G. Percoco, M. A. Ragolia, G. Stano, e A. Di Nisio. 2022. “Additive Manufacturing for Sensors: Piezoresistive Strain Gauge with Temperature Compensation”. *Applied Sciences (Switzerland)* 12(17). doi: 10.3390/app12178607.

Li, L., Q. Sun, C. Bellehumeur, e P. Gu. 2002. “Composite Modeling and Analysis for Fabrication of FDM Prototypes with Locally Controlled Properties”. *Journal of Manufacturing Processes* 4(2):129–41. doi: 10.1016/S1526-6125(02)70139-4.

Liu, Jikai, Jingjing Yan, e Huangchao Yu. 2021. “Stress-constrained topology optimization for material extrusion polymer additive manufacturing”. *Journal of Computational Design and Engineering* 8(3):979–93. doi: 10.1093/jcde/qwab028.

Magnoni, P., L. Rebaioli, I. Fassi, N. Pedrocchi, e L. M. Tosatti. 2017. “Robotic AM System for Plastic Materials: Tuning and On-line Adjustment of Process Parameters”. *Procedia Manufacturing* 11:346–54. doi: 10.1016/j.promfg.2017.07.117.

Moreno Nieto, D., V. Casal López, e S. I. Molina. 2018. “Large-format polymeric pellet-based additive manufacturing for the naval industry”. *Additive Manufacturing* 23:79–85. doi: 10.1016/j.addma.2018.07.012.

Pandey, Pulak M., N. Venkata Reddy, e Sanjay G. Dhande. 2003. “Improvement of surface finish by staircase machining in fused deposition modeling”. *Journal of Materials Processing Technology* 132(1–3):323–31. doi: 10.1016/S0924-0136(02)00953-6.

Rebaioli, Lara, Paolo Magnoni, Irene Fassi, Nicola Pedrocchi, e Lorenzo Molinari Tosatti. 2019. “Process parameters tuning and online re-slicing for robotized additive manufacturing of big plastic objects”. *Robotics and Computer-Integrated Manufacturing* 55:55–64. doi: 10.1016/j.rcim.2018.07.012.

Reich, Matthew J., Aubrey L. Woern, Nagendra G. Tanikella, e Joshua M. Pearce. 2019. “Mechanical properties and applications of recycled polycarbonate particle material extrusion-based additive manufacturing”. *Materials* 12(10). doi: 10.3390/ma12101642.

Shenoy, Aroon V. 1999. *Rheology of Filled Polymer Systems*. Dordrecht: Springer Netherlands.

Shi, Yuan, Xiaotian (Dennis) Wu, Joseph A. Paydarfar, e Ryan J. Halter. 2021. “Imaging-compatible oral retractor system for use in image-guided transoral robotic surgery”. P. 4 em *Medical Imaging 2021: Image-Guided Procedures, Robotic Interventions, and Modeling*, organizado por C. A. Linte e J. H. Siewerdsen. SPIE.

Sun, Cheng, Yun Wang, Michael D. McMurtrey, Nathan D. Jerred, Frank Liou, e Ju Li. 2021. “Additive manufacturing for energy: A review”. *Applied Energy* 282. doi: 10.1016/j.apenergy.2020.116041.

Tang, Shi-yan, Li Yang, Zi-tian Fan, Wen-ming Jiang, e Xin-wang Liu. 2021. “A review of additive manufacturing technology and its application to foundry in China”. *China Foundry* 18(4):249–64. doi: 10.1007/s41230-021-1003-0.

Thompson, Mary Kathryn, Giovanni Moroni, Tom Vaneker, Georges Fadel, R. Ian Campbell, Ian Gibson, Alain Bernard, Joachim Schulz, Patricia Graf, Bhrigu Ahuja, e Filomeno Martina. 2016. “Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints”. *CIRP Annals* 65(2):737–60. doi: 10.1016/j.cirp.2016.05.004.

Walia, Kartikeya, Ahmed Khan, e Philip Breedon. 2021. “Polymer-Based Additive Manufacturing: Process Optimisation for Low-Cost Industrial Robotics Manufacture”. *Polymers* 13(16):2809. doi: 10.3390/polym13162809.

Wang, Zhiyuan, Renwei Liu, Todd Sparks, e Frank Liou. 2016. “Large-Scale Deposition System by an Industrial Robot (I): Design of Fused Pellet Modeling System and Extrusion Process Analysis”. *3D Printing and Additive Manufacturing* 3(1):39–47. doi: 10.1089/3dp.2015.0029.

Woern, Aubrey L., e Joshua M. Pearce. 2018. “3-D printable polymer pelletizer chopper for fused granular fabrication-based additive manufacturing”. *Inventions* 3(4). doi: 10.3390/inventions3040078.

Yaragalla, S., M. Zahid, J. K. Panda, N. Tsagarakis, R. Cingolani, e A. Athanassiou. 2021. “Comprehensive enhancement in thermomechanical performance of melt-extruded peek filaments by graphene incorporation”. *Polymers* 13(9). doi: 10.3390/polym13091425.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.