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# Printing parameter optimization of PLA material concerning geometrical accuracy and tensile properties relative to FDM process productivity

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**Abstract** High demand for part customization shifts industries toward AM technologies. Part customization in high-volume manufacturing is developed to its limits, whereas low-volume production using AM is still economically unjustified. FDM technology is quite common in low-volume AM production, but the main issue is poor printing parameter optimization which may result in insufficient final part quality. The subject of this paper is the experimental determination of the optimal parameters for the PLA polymer FDM parts, focusing on nozzle temperature and printing speed. Part geometry and mechanical properties are evaluated for the temperature range of 170-210 °C and speeds of 40, 80, and 120 mm/min. Roughness measurements for part geometrical accuracy assessment and tensile tests for mechanical property estimation have shown the clear advantage of 190 °C and 40 mm/min over the other parameter combinations. However, for higher FDM process productivity 80 mm/min speed may also be considered with 190 °C.

## 1. Introduction

Nowadays, FDM is the most commonly used AM technology, reaching from household non-professional devices to high-end industrial machines. This particular technology uses thermoplastic polymers, such as PLA, ABS, PET, PP, etc. [1, 2]. What distinguishes PLA from the rest of the FDM thermoplastics is its high dimensional accuracy of final printed parts and the fact that this material has eco-friendly nature. The last implies a renewable resource origin of the PLA material, thus PLA printing material may be created from derivatives such as cassava roots, corn starch, etc. This also means that this material is highly recyclable [3, 4].

FDM technology is an extrusion-based AM technology where polymer material is melted and deposited onto a horizontally placed platform until a certain layer is created. After one layer creation, accurate downward displacement of the printing bed allows the nozzle to create another layer. By repeating this process, in the so-called “layer-by-layer manner'' printing continues until the part is finished (Fig. 1). Thermoplastics used in FDM have to be in the form of a round cross-section filament. The filament is guided through the extruder from the tensioner and feeder wheel pair to the thermal block, where the filament is heated at a predefined temperature above the materials melting point, and finally extruded through the nozzle onto a printing bed. The stepper motor is usually connected to the feeder wheel, providing the motion for this process. The tensioner wheel is used for filament gripping. To perform the heating and to maintain the set temperature, the thermal block is equipped with a heater and a thermocouple. In order to prevent the filament from melting before reaching the thermal block, the nozzle throat is placed inside a heatsink. Its function is to dissipate heat from the nozzle throat, thus preventing clogging inside of an extruder. Some FDM machine designs have installed fans around the heatsink to improve heat dissipation. Besides the extrusion process, other stepper motors control the extrusion path of the melted material from the nozzle onto a printing bed,

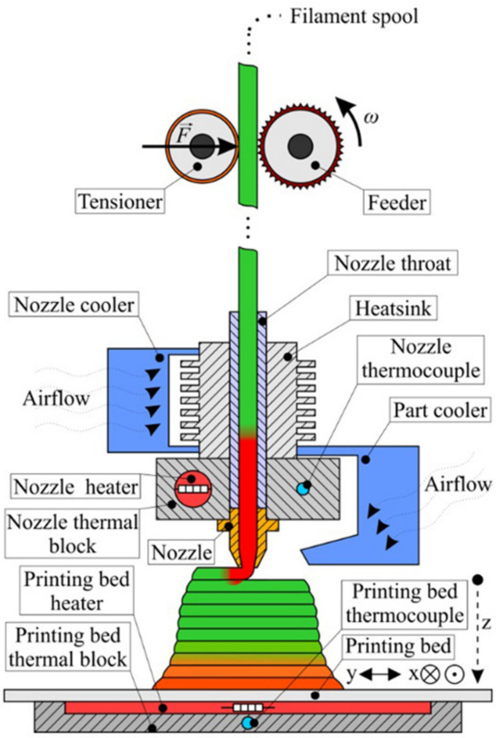



Fig. 1. FDM process schematic.

and one particular set of motors controls the vertical (Z-axis) movement of the printing bed. This set of stepper motors performs the downward printing bed movement in order to allow for the next layer to be created [2, 3, 5]. Worth mentioning is that for some materials it is advisable to have heaters and thermocouples installed beneath the printing bed to hold a certain temperature of the first material layers, in order to prevent peeling of the material from the printing bed. For sufficient adhesion of the material, it is advisable to maintain the printing bed surface temperature a little over the glass transition temperature of the polymer. For example, ABS polymer requires temperatures around 100 °C, while the PLA polymer which is a subject of this research, requires temperatures around 60 °C [2, 5-7].

Geometrical accuracy and mechanical properties of parts produced via FDM technology are highly dependent on the chosen printing parameters, thus many research papers nowadays are focused on printing parameter optimization in order to achieve parts with satisfactory properties, both in terms of part dimensional accuracy and mechanical properties [3, 4, 6, 8-21].

FDM part geometrical accuracy is evaluated using specific benchmark models which are measured using vernier calipers, 3D scanners, CMMs, or surface roughness measuring instruments, and obtained dimensions via such devices are compared with original CAD models [6, 8-11]. Such geometrical comparations can be performed using commercial software [8-10] or by developing their own software solutions [11].

Concerning the tensile properties of FDM parts, a few printing parameters stand out, in order to achieve better mechanical properties, such as layer thickness, infill density, raster orientation, nozzle temperature, and printing speeds [12-21]. The main issue with FDM parts is the weak bonding between layers, due to the higher ratio of air gaps placed in-between adjacent layers and strands, which is the case with higher layer thicknesses. The best recommendation is to use lower layer thickness but to be careful not to cause over-compression of layers, which except for mechanical properties may also affect the geomaterial accuracy of the part [12-16]. Chosen raster orientation may influence the mechanical properties of the FDM part, but it is dependent on the load direction. For tensile tests, the recommendation to achieve higher UTS values is to print strands in the direction of the load [15, 18]. Raster orientation doesn't have a notable impact on Young's modulus [15, 19]. Infill density has an obvious influence on the mechanical properties of the part, hence denser FDM parts contain more material to resist loads [20]. But, higher infill density FDM parts require more time to be produced, thus lowering the productivity of the FDM process.

The main concern of this research paper is the influence of nozzle temperature and printing speed. Higher nozzle temperatures improve the UTS due to better fusion and improved adjacent layer cohesion, resulting in a lesser number and volume of air gaps that are present in FDM parts [1, 12-16, 20]. With satisfactory printing parameter optimization, a near-homogeneous structure can be achieved [12-14], mostly because of applied nozzle temperatures. What concerns the most is that PLA material is a widely used material in FDM nowadays [1-4], but FDM parts made from particular material have the highest ratio of air gaps in their cross-sections compared to other thermoplastics [1]. Next, printing speed is the most influential printing parameter concerning FDM process productivity, hence higher the speeds are, the less time it takes for the FDM machine to finish the part. However, lower speeds allow for better bonding between layers and strands [1, 21]. As stated before, both nozzle temperature and printing speed have an influence on bonding between layers of created FDM part, thus this research focuses on both of these printing parameters.

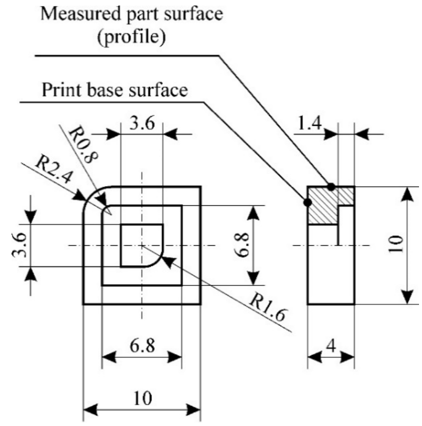
FDM parts need to have low dimensional tolerances and certain mechanical properties in order to resist loads to be considered for functional applications. Hence, they must have good geometrical accuracy, and sufficient mechanical properties, such as stiffness, UTS, and enough plasticity reserve in order to fulfill such tasks [1, 12, 15, 17, 19, 20].

## 2. Materials and methods

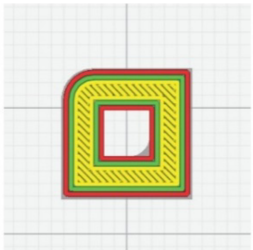
The experimental plan is to conduct experiments in two stages namely, the first stage refers to FDM part geometrical accuracy examination, and the second stage involves the evaluation of part mechanical properties. Therefore, tensile tests are conducted for this material. All PLA parts have been additively manufactured using Anycubic i3 Mega device (Shenzhen Anycubic Technology Co., Ltd., Shenzhen, China),

Table 1. Printing parameter combination.

| Part no. | Printing speed $v_P$ [mm/min] | Nozzle temperature $T_P$ [°C] | Printing bed temperature $T_{PB}$ [°C] |
|---|---|---|---|
| 1 | 40 | 170 | 60 |
| 2 | 80 | | |
| 3 | 120 | | |
| 4 | 40 | 180 | |
| 5 | 80 | | |
| 6 | 120 | | |
| 7 | 40 | 190 | |
| 8 | 80 | | |
| 9 | 120 | | |
| 10 | 40 | 200 | |
| 11 | 80 | | |
| 12 | 120 | | |
| 13 | 40 | 210 | |
| 14 | 80 | | |
| 15 | 120 | | |




(a)



(b)

Fig. 2. (a) Benchmark model engineering drawing (units in mm); (b) 3D printing infill pattern.

developed under the open-source Prusa i3 platform (RepRap project, GNU General Public License). Because PLA material can be affected by moisture [1], all FDM parts have been stored, (geometrically) measured and tensile tested on RT and relative humidity of 50 %.

For the examination of PLA material's geometrical accuracy first, the benchmark model is created in dedicated CAD software (SolidWorks, Dassault Systèmes, Vélizy-Villacoublay, France), as in previous research [6, 8-11]. The engineering drawing of a particular benchmark model is shown in Fig. 2(a). In order to evaluate printing speed and nozzle temperature influence on FDM part geometrical accuracy, fifteen parts are generated with different combinations of printing parameters, which are shown in Table 1.

Here, the nozzle temperature range is from 170 °C to 210 °C with an increment of 10 °C, i.e., five nozzle temperatures in total. Each nozzle temperature is combined with all three chosen printing speeds, i.e., 40, 80, and 120 mm/min. Regarding the selection of printing speeds, most of the mentioned research for PLA material has printing speeds that fall within this selected range [1, 12-16, 19]. Just to mention, some research papers [20, 21] also include a printing speed of 30 mm/min. The rectilinear infill pattern on the benchmark model is presented in Fig. 2(b).

To prevent unwanted peeling of the first printed layer, the FDM machine's printing bed was preheated to 60 °C for all parts. Also, the nozzle diameter is 0.4 mm, for all parts. Even though layer thickness has an influence on geometrical accuracy [6, 10] and tensile properties [1, 12-15, 20] only one layer thickness is applied, due to the impracticality of including one more printing parameter which would double or triple the number of required parts. According to Refs. [12-14], the layer thickness of 0.2-0.25 mm is optimal for conceiving a satisfactory level of cohesion between strands. Hence, 0.2 mm is selected due to good experience from the previous work of the authors [11].

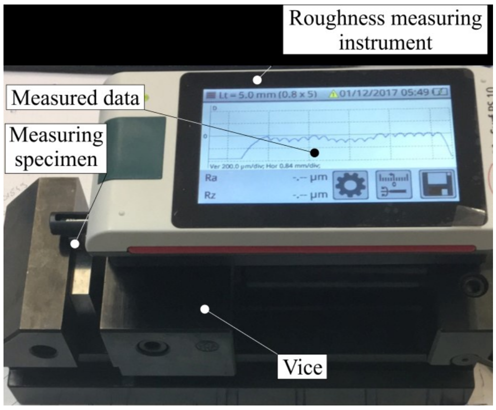



Fig. 3. Experimental setup for examination of geometrical accuracy of printed parts.

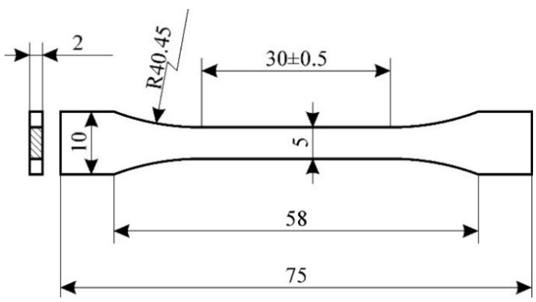
After the AM of parts, specimens are inspected using an optical stereo microscope Motic DM-143 (Motic, Xiamen, China), equipped with an integrated camera and software, in order to analyze the bonding between layers and to track any possible imperfections, due to the influence of printing parameters.

For the examination of the geometrical accuracy of FDM parts, surface profiles are measured with the roughness measuring instrument MahrSurf PS10 (Mahr GmbH, Goettingen, Germany), see Fig. 3. MahrSurf PS10 uses the stylus method as the measuring principle. Here, the specimen is fixed in the vice, and afterward, the probe travels across the targeted part length, specified on the Fig. 2(a) as "measured part surface (profile)". The results of these measurements are roughness profiles, i.e., diagrams showing profile deviation relative to the measured length (see "measured data" in Fig. 3).

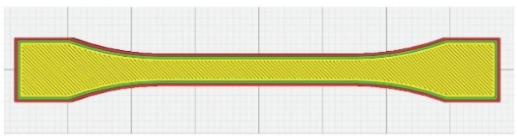
Tensile tests are conducted according to the ISO 527-2:2019 standard, using specimen type A12 (Fig. 4(a)), with printing parameter combination as in Table 1. All specimens have 100 % infill density and stated 0.2 mm layer thickness. Same as for the benchmark model shown in Fig. 2(b), the used infill pattern for the tensile specimens is shown in Fig. 4(b).

Tensile tests are performed on the universal testing machine Shimadzu Autograph AGS-X (Shimadzu Corp., Kyoto, Japan), equipped with a load cell with 100 kN capacity and clamps for tensile testing (Fig. 5). As in research Ref. [22] extensometer device is not used, due to potential problem of extensometer influence on the final results. Namely, polymers are usually not fit for extensometer application, because of their insufficient mechanical properties compared to metals from which extensometer contacts are made. Thus, extensometer gripping during tensile testing may create cuts on the specimen at points of contact. Instead, displacement values have been taken from the machine's crosshead movement and used to calculate the Elastic modulus. This method does not provide accurate value estimation but can be used to assess printing temperature and speed influence on the stiffness of printed parts.

All tensile specimens are tested in stroke control of 1 mm/min, according to ISO 527-2:2019 standard. Just to emphasize that PLA material has near strain-rate independent behavior [1]. Three tensile specimens are prepared for each testing batch.




(a)



(b)

Fig. 4. (a) ISO 527-2:2019 tensile specimen type A12 (units in mm); (b) 3D printing infill pattern.

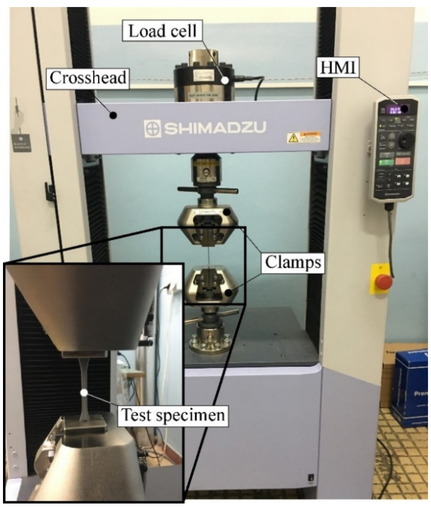



Fig. 5. Universal tensile testing machine Shimadzu Autograph AGS-X, 100 kN capacity.

## 3. Results and discussion

FDM is known for slow manufacturing speeds and poor surface quality [23]. Printing orientation influence is confirmed by Ref. [24], showing a range from 1 to 7 μm. This research focuses on the influence of two other important printing parameters on the surface quality of final printed parts, namely printing speed and temperature. Optical microscopy is used to analyze PLA material bonding between layers, showing that chosen printing conditions have an effect on the part surface, see Fig. 6.

As can be seen in Fig. 6, the increase in the printing speed led to a decrease in the bonding between the layers. Such a phenomenon leads to an increase in the air gap formation between the layers, which has an effect on the lower adhesion between layers of the FDM part [25], as well as on the violated integrity of the printed structure itself. This is especially pronounced at the points of nozzle direction change, where the deviation of the part geometry is expressed by the fact that unwanted radii are more visible in parts printed at higher speeds. Optical microscopy analysis shows that the density of the air gaps between the layers is not influenced by the melting, i.e., nozzle temperature (Fig. 6). This is mainly related to the use of the part cooler in this particular case therefore, FDM parts regardless of temperature were evenly cooled.

According to the roughness measurement profiles, i.e., diagrams presented in Fig. 7, chosen printing parameters have a significant influence on the part profile accuracy. It can be seen from the image that at the lower printing speed, a better part profile is achieved. For example, research papers [24, 25] only include 190 °C temperature, but here a nozzle temperature range is from 170 to 210 °C. Results show that with an increase in the nozzle temperature, printing speed has much more influence on the part profile. This can be explained by the fact that polymer materials have lower viscosity at higher temperatures [12] thus for better part consistency, lower speeds have to be applied. Namely, the best geometrical accuracy of the FDM part profiles is achieved with the lowest printing speed, i.e., 40 mm/min. Furthermore, an increase in the printing speed

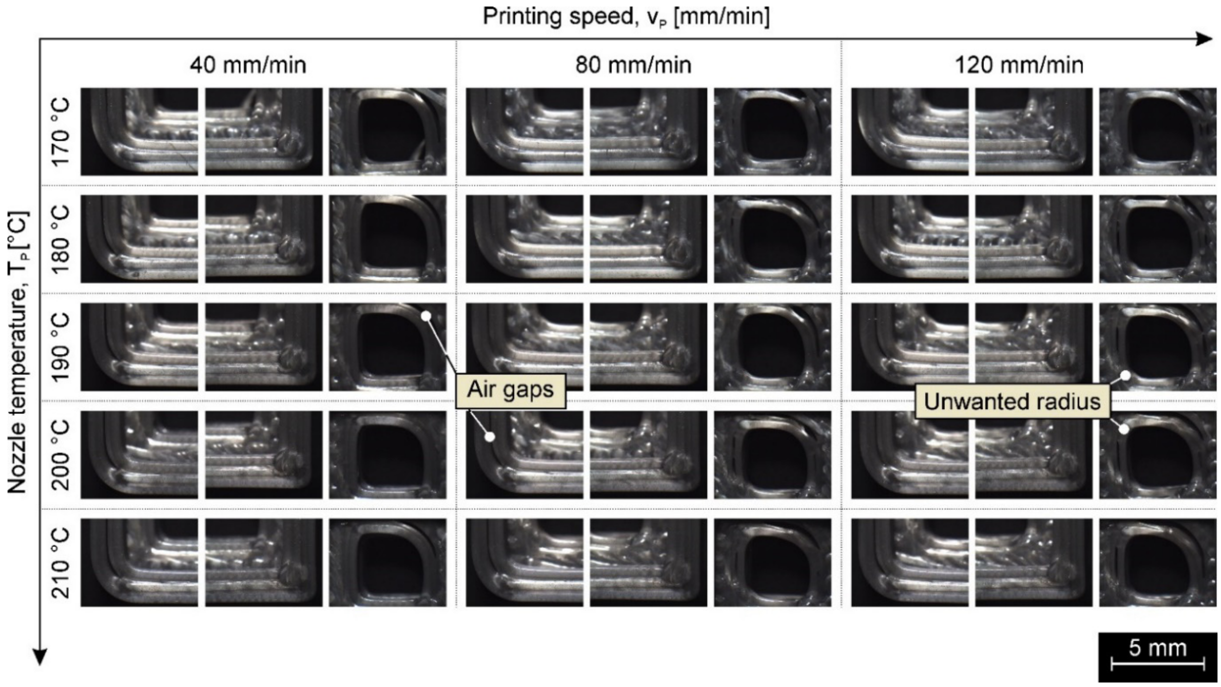



Fig. 6. Optical microscopy of the FDM benchmark model, relative to the nozzle temperature and printing speed.

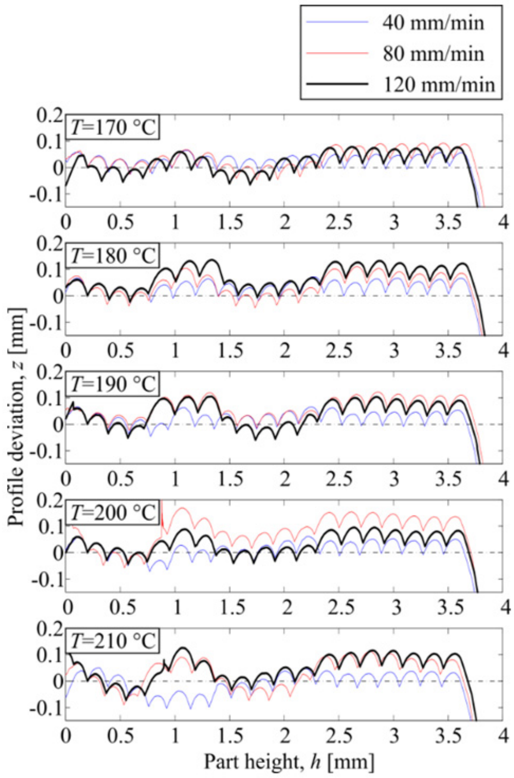



Fig. 7. Part surface deviation relative to the nozzle temperature and printing speed.

leads to a higher deviation of the profiles. Lower nozzle temperatures have to be set in order to acquire the best geometrical accuracy results of the part profiles. Thus, the increase in the nozzle temperature value brings a higher dependence on the FDM part profile's geometrical accuracy from the printing speed.

For this statement, only one benchmark part per each printing condition was used with confidence in the FDM machine's repeatability, which was tested in the previous research [11].

With the increase of the nozzle temperature value, a longer time is needed for the layer to be fully cooled. During this time polymer is in a semiliquid state, which directly impacts the height of the final FDM part. The higher the nozzle temperature, the greater the degree of layer deformation.

If the main goal is to acquire the best geometrical accuracy results recommended nozzle temperature has to be no higher than 190 °C. Hence, according to this research findings, research papers [24, 25] have set an optimal printing temperature concerning the geometrical accuracy of the final parts. In order to increase the productivity of the FDM process, but still, maintain sufficient geometrical accuracy for PLA polymer, the recommendation is to use lower nozzle temperatures, where printing speeds have no significant impact on the FDM part geometrical accuracy.

Recommended optimal printing parameters lead to the acquisition of sufficient geometrical accuracy of the FDM part, but it still doesn't mean that adequate structural integrity of the FDM part will be achieved.

Tensile tests are conducted in order to investigate the influence of chosen printing parameters on the structural integrity of the FDM parts. In previous research conducted by Refs. [26, 27], extrusion temperatures and speeds have proven to have a significant influence on mechanical properties. Reduction in the extrusion volume is present at higher printing speeds, thus

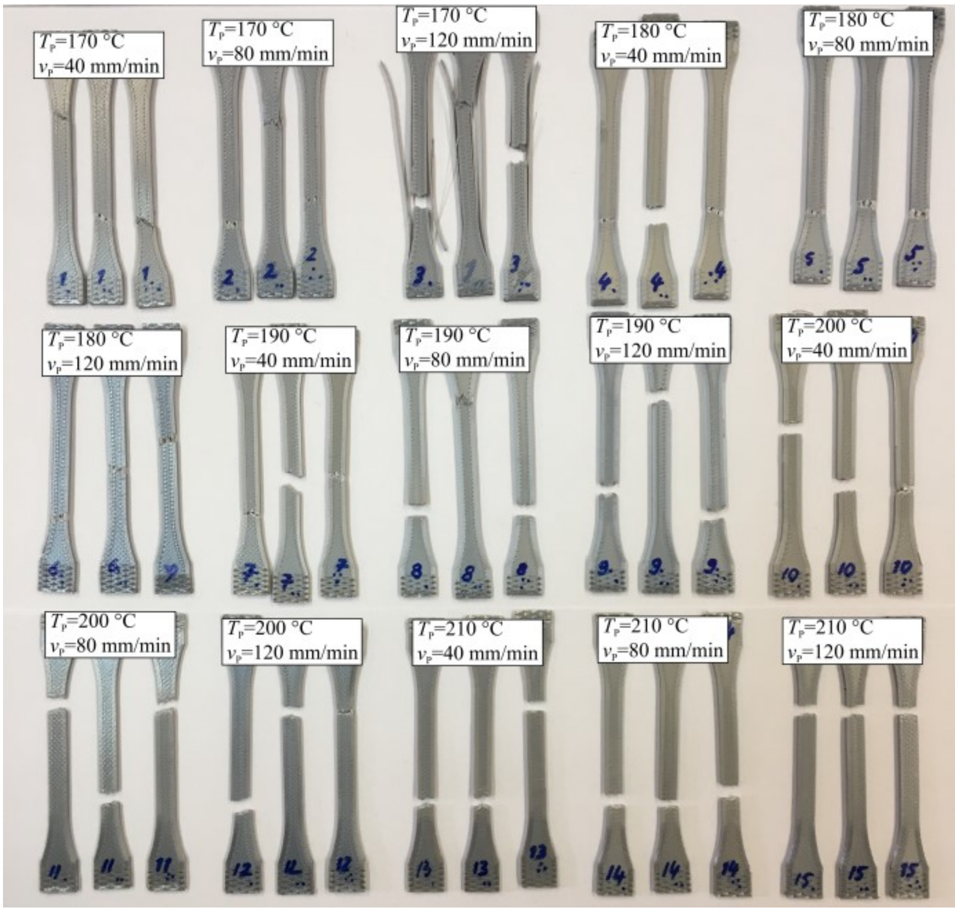



Fig. 8. Tensile test specimens.

UTS and elastic modulus have lower values [26]. Higher extrusion temperatures have shown significant benefits regarding mechanical properties [12, 27]. Even with other AM technologies temperatures have shown the greatest impact [28, 29]. The novelty of this research is the consideration of both the extrusion temperature and printing speed in a single research paper, in order to estimate their joint influence on geometrical accuracy and mechanical properties.

All tested specimens are shown in Fig. 8, with all tensile specimen batches labeled. The combination of the lowest nozzle temperature and printing speed (170 °C and 40 mm/min, respectively) results in partial specimen fracture, i.e., there are no signs of total specimen failure. More precisely, tested specimens show significant plastic deformation, having obviously lost their integrity, i.e., a drop in force on the testing machine is reached but the specimens haven't broken into two pieces. With the highest printing speed (120 mm/min), fracture surfaces are clearly visible, with distinct delamination of outer layers. Tested specimens additively manufactured with nozzle temperatures from 180 to 190 °C show partial brittle and ductile fracture. For nozzle temperatures exceeding 190 °C, only brittle fracture is present. According to this research findings nozzle temperatures influence the nature of fracture surfaces in such a way that higher nozzle temperatures during FDM part manufacturing favored the brittle fracture.

All acquired stress-strain diagrams from tensile tests are presented in Fig. 9(a). For the lowest nozzle temperature (170 °C), printing speeds have a noticeable influence on the average UTS values. Here, the average UTS ranges from 40.61 to 49.18 MPa, depending on the printing speed. With higher nozzle temperatures (higher than 190 °C) average UTS is also higher, but the difference between the individual values is less pronounced. Here, UTS values are around 55 MPa. An increase in printing speeds creates a decrease in average UTS, as in Refs. [21, 26]. However, this trend is less noticeable at higher nozzle temperatures, i.e., at 190 °C or higher. Hence, nozzle temperatures from 190 °C-onward, leave out the dependence between average UTS values and printing speeds, which is better visualized in Fig. 9(b). Worth mentioning is that UTS results here are comparable with the previous research findings, where all the UTS values from any printing condition range from 38 to 57 MPa [24, 30, 31].

Regarding failure strain values (Figs. 9(a) and 10), higher nozzle temperatures increase the average value. With lower printing speeds overall, straining is higher. This results in pronounced yielding and larger plastic deformations on fractured surfaces of tested specimens, as in Ref. [1]. Higher printing speeds aspire specimens to fail in a brittle manner, as can also

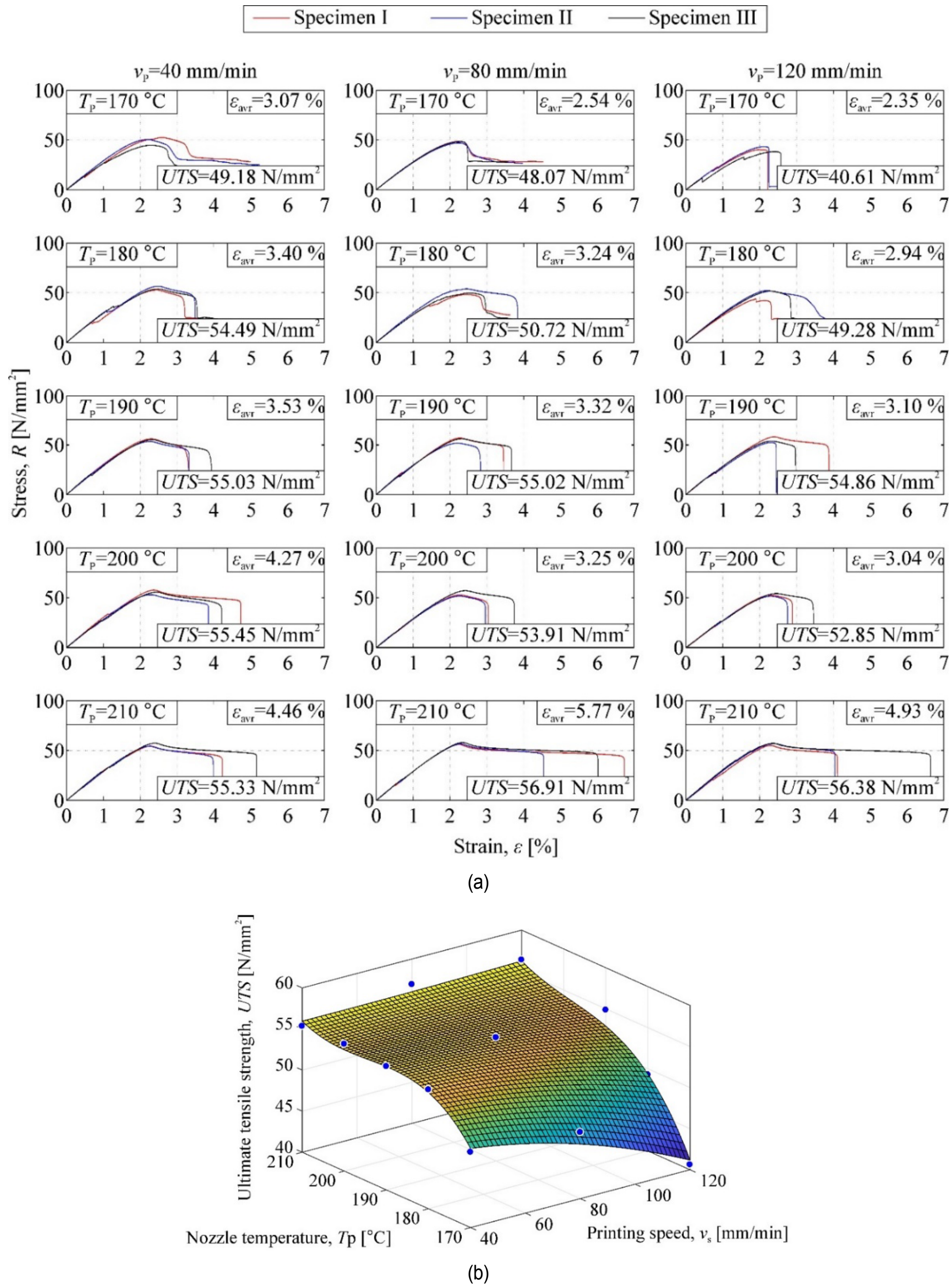



Fig. 9. (a) Stress-strain curves for PLA material relative to set printing conditions; (b) dependence of the *UTS* relative to the printing conditions.

be recognized from stress-strain diagrams in Fig. 9(a). Likewise, with lower nozzle temperatures this trend is more noticeable than in specimens created using higher temperatures. Also, as can be seen from Fig. 10, lower printing speeds are less dependent on nozzle temperatures, regarding straining. Here, 80 and 120 mm/min printing speeds have a noticeably higher dependency on temperature values than 40 mm/min.

Elastic modulus values depend on the nozzle temperatures and printing speeds, see Fig. 11. Here, a nozzle temperature of 190 °C creates the maximum value, which is the case for printing speeds of 40 and 80 mm/min. After exceeding 190 °C elastic modulus tends toward a constant value for 80 mm/min, and for 40 mm/min there is a value drop. For the highest printing speed (120 mm/min) there are no intermediate peaks in this temperature interval. Lower printing speeds result in higher Elastic modulus values, meaning that the FDM parts are stiffer. But, for temperatures higher than 190 °C elastic modulus is susceptible to value decline at lower printing speeds, due to PLA material deterioration influenced by longer exposure to high temperatures.

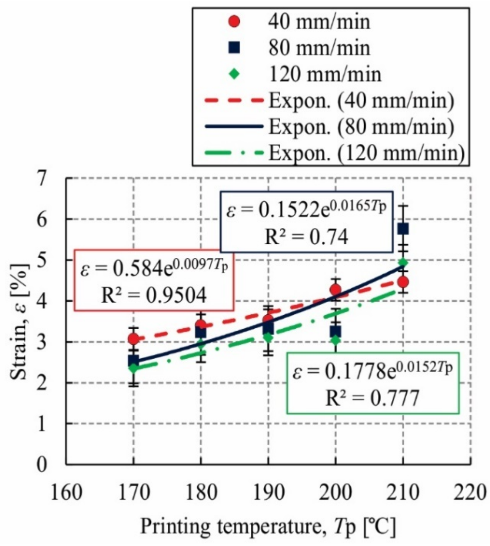



Fig. 10. Failure strain values, relative to set printing conditions.

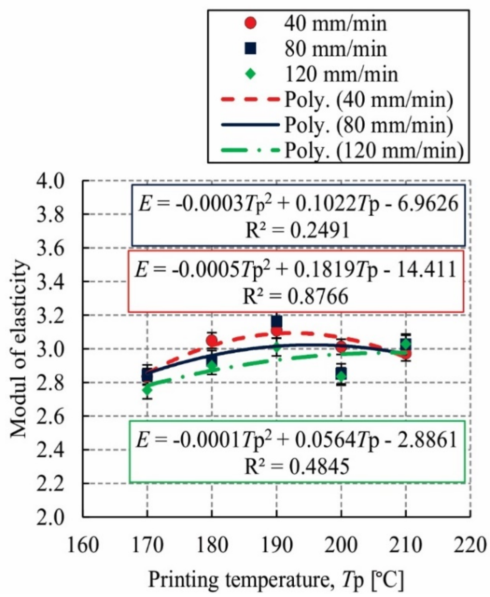



Fig. 11. Elastic modulus values, relative to set printing conditions.

On the basis of all the stated above, the impact of all these printing conditions can be estimated also on the toughness of this material, by knowing that stiffness, UTS, and final strain value have an influence on the surface underneath the stress-strain curve, which is one way to estimate toughness [4]. Lower printing speeds result in greater UTS, higher straining, and stiffness. Then, higher UTS values are expected with higher nozzle temperatures. Thus, printing regimes to consider are 40 mm/min speed combined with temperatures from 190 to 210 °C. Research paper [27] presented the best combination for achieving the highest toughness, thus stating that 200 °C is the most beneficial extrusion temperature. Also, because stiffness has a near constant and high value for 80 mm/min after 190 °C, and due to high strain values here, all three conditions with a temperature range from 190 to 210 °C with 80 mm/min may be considered.

## 4. Conclusions

In order to acquire optimal geometry of the FDM part, but in the same way to maintain the necessary integrity of the structure, a detailed experimental analysis has to be conducted. In this paper, experimental determination of optimal printing conditions for parts made from PLA polymer, considering nozzle temperatures and printing speeds, is implemented.

In order to obtain sufficient geometrical accuracy of PLA parts, it is a recommendation to use nozzle temperatures in the range of 170 up to 190 °C. If higher FDM process productivity is one of the demands, the recommendation from this research findings is to use lower melting temperatures, at which printing speeds do not affect the geometry of the part.

Concerning tensile properties of the PLA part, higher UTS is achieved with higher melting, i.e., nozzle temperatures. Printing speeds have a noticeable influence on UTS until 190 °C, after which they have less noticeable influence. Strain and stiffness are also dependent on these conditions. Higher straining is achieved with lower printing speeds, and values are higher with higher nozzle temperatures. Regarding the elastic modulus, at 190 °C temperature, it holds a maximum value for 40 mm/min, and for 80 mm/min at higher temperatures than 190 °C, it has a nearly constant value. Also, worth mentioning is that higher temperatures result in brittle fracture surfaces on specimens.

The influence of all these tensile properties can be combined into one parameter - toughness. For any functional use of FDM parts, this is probably the worthiest parameter to be considered. Here, optimal printing parameters considering mechanical properties are temperatures in the range from 190 to 210 °C with 40 and 80 mm/min speeds.

Finally, conclusion is that the best combination of these parameters, concerning geometrical accuracy and mechanical properties, is the nozzle temperature of 190 °C with 40 mm/min speed. As for the FDM process productivity, 80 mm/min speed may be considered, due to the low difference between these two speeds regarding stiffness, UTS, and final strain values for 190 °C temperature.

## Acknowledgments

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## Nomenclature

*AM* : Additive manufacturing
*FDM* : Fused deposition modeling

*PLA* : Polylactic acid
*ABS* : Acrylonitrile butadiene styrene
*PET* : Polyethylene terephtalate
*PP* : Polypropylene
*CMM* : Coordinate-measuring machine
*CAD* : Computer-aided design
*UTS* : Ultimate tensile strength
*RT* : Room temperature

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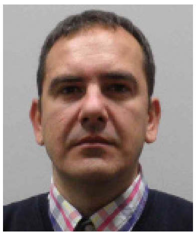

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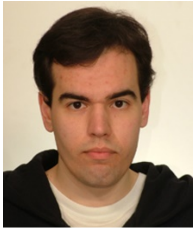

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