The Influence of the Process Parameters on the Mechanical Properties of PLA Specimens Produced by Fused Filament Fabrication—A Review

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Abstract: Polylactic acid (PLA) is produced from renewable materials, has a low melting temperature and has a low carbon footprint. These advantages have led to the extensive use of polylactic acid in additive manufacturing, particularly by fused filament fabrication (FFF). PLA parts that are 3D printed for industrial applications require stable mechanical properties and predictability regarding their dependence on the process parameters. Therefore, the development of the FFF process has been continuously accompanied by the development of software packages that generate CNC codes for the printers. A large number of user-controllable process parameters have been introduced in these software packages. In this respect, a lot of articles in the specialized literature address the issue of the influence of the process parameters on the mechanical properties of 3D-printed specimens. A systematic review of the research targeting the influence of process parameters on the mechanical properties of PLA specimens additively manufactured by fused filament fabrication was carried out by the authors of this paper. Six process parameters (layer thickness, printing speed, printing temperature, build plate temperature, build orientation and raster angle) were followed. The mechanical behavior was evaluated by tensile, compressive and bending properties.

Keywords: polylactic acid (PLA); fused filament fabrication (FFF); mechanical properties; process parameters

1. Introduction

Additive manufacturing (AM) technologies are increasingly used for component fabrication and tend to become an essential topic of the Industry 4.0 concept [1]. These technologies shorten the manufacturing time, thereby allowing the rapid transition from 3D models to real parts. Using additive manufacturing, both the external and the internal geometry of components can be optimized. The optimization of the internal geometry of parts allows for an efficient material distribution, correlated to the stress state.

The ISO/ASTM 52900:2015 standard [2] defines the following categories of processes used for additive manufacturing of polymers: material extrusion, material jetting, powder bed fusion, binder jetting, vat photo-polymerization and sheet lamination.

Fused filament fabrication (FFF) is a material extrusion process in which the part is built up by successive layers, each of them being made line by line. The material, in the form of a continuous filament, is melted and deposited by a printing head with a nozzle. Fused filament fabrication (also known as fused deposition modeling) is currently one of the most widely used additive technologies [1]. A great variety of equipment has been developed for the FFF technology, ranging from industrial and laboratory use to office and hobby applications.

The advantages of fused filament fabrication are based on the simplicity of the process and on the low cost of materials, equipment and consumables [3]. For the widespread
use of fused filament fabrication for industrial manufacturing, it is necessary to obtain printed products with predictable properties. The following categories of AM product requirements are defined by ISO 17296-3:2014 [4]:

- Surface requirements: surface texture, appearance, color;
- Geometric requirements: linear and angular dimensions, dimensional tolerances, geometrical tolerances (deviations in shape and relative position);
- Mechanical requirements: hardness, tensile strength, impact strength, compressive strength, flexural strength, fatigue strength, creep, ageing, frictional coefficient, shear resistance and crack extension;
- Build material requirements: density, physical properties and chemical properties.

The mechanical properties of components obtained by fused filament fabrication are influenced not only by the material properties, but also by the characteristics of the 3D printer, the process parameters and the post-process treatments [5–9].

The 3D model conversion for the printing process is achieved by using a slicer software (a G-code generation software, specific to the printing process). This software allows for setting the values for a large number of process parameters, the most frequently analyzed being the following [6]:

- Slicing parameters: layer thickness, printing speed/flow rate, nozzle diameter, raster parameters, number of wall lines, wall thickness, top layer thickness, bottom layer thickness;
- Temperature parameters: printing head temperature, build plate temperature, build volume temperature (printer with/without closed space), cooling;
- Infill parameters: infill density and infill pattern;
- Build orientation parameters and the use of support material.

Polylactic acid (PLA) is a thermoplastic polyester that can be obtained from renewable resources at a low production cost. PLA has a low melting point, making it easy to use in most FFF equipment. The extrusion temperature of PLA is lower than that of other common polymeric materials (ABS—acrylonitrile butadiene styrene, PEEK—polyether ether ketone, PETG—polyethylene terephthalateglycol), and its tensile strength and elastic modulus may be superior to ABS and PET-G [10–13]. Furthermore, PLA is biodegradable, has a low carbon footprint and low smoke emissions during extrusion [13] and can be successfully used in medical applications, because it is not metabolically harmful [14].

The influence of the process parameters on the mechanical properties of PLA specimens obtained by fused filament fabrication has been intensively studied in recent years. In the research carried out so far, one to five process parameters have been varied. Statistical methods, such as design of experiments (DOE), the Taguchi method, and analysis of variance (ANOVA) were used to determine the influence of the different parameters on the mechanical characteristics [15,16].

In order to understand the effect of each of these numerous parameters, as well as the correlation between them, a systematic analysis of the published research is necessary. Therefore, the goal of this paper is to present an up-to-date review of the literature targeting the influence of the process parameters on the mechanical properties of PLA specimens, made by fused filament fabrication. The analysis focused on the variation of the following parameters: layer thickness, printing speed, printing head temperature, build plate temperature, build orientation and raster angle. For the characterization of the static mechanical behavior, the results of tensile, bending and compression tests were followed. The literature review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

The search terms used in bibliographic databases to select the analyzed papers were as follows: (PLA OR "poly$lactic") AND (FDM OR FFF OR "fused") AND (mechanical OR tensile OR bending OR strength). Papers dealing with the dynamic behavior of PLA, with PLA-based composites or only with the variation of mechanical properties as a function of the infill pattern and the infill density were not included in the present review. As
the variation of mechanical properties according to the type of infill has been intensively studied, an analysis of the influence of the infill pattern and the infill density on the mechanical behavior of printed parts will be presented by the authors in a separate paper.

Table 1 shows the notations and abbreviations used in this paper to define the process parameters and mechanical characteristics.

Table 1. Notations and abbreviations.

| Process Parameter                                      | Notation | Units |
|--------------------------------------------------------|----------|-------|
| Layer thickness (layer height)                         | t        | (mm)  |
| Printing speed                                         | \( s_p \) | (mm/s) |
| Printing head (nozzle) temperature                     | \( T_{H} \) | (°C)  |
| Build plate temperature                                | \( T_{B} \) | (°C)  |
| Nozzle diameter                                        | \( d_n \) | (mm)  |
| Filament diameter                                      | \( d_f \) | (mm)  |
| Build orientation (acc. to ISO/ASTM 52921:2013 [17])  | XY, XZ, YX, YZ, ZY | (-) |
| Build orientation angle in the xy plane (around the z-axis) where angle is measured (\( \alpha_{ZX} = 0° \) correspond to ZX build orientation) | \( \alpha_{XY}, \alpha_{XY}, \alpha_{XZ} \) | (°) |
| Build orientation angle in the yz plane (around the x-axis) | \( \beta_{XY}, \beta_{YX}, \beta_{YX} \) | (°) |
| Build orientation angle in the xz plane (around the y-axis) | \( \gamma_{ZX}, \gamma_{XY}, \gamma_{XZ} \) | (°) |
| Raster angle                                           | \( \theta \) | (°)   |
| Number of wall lines                                   | \( W_L \) | (-)   |
| Tensile/bending test speed                             | \( s_t \) | (mm/min) |
| Ultimate tensile strength                              | UTS      | (MPa) |
| Ultimate flexural strength                             | UFS      | (MPa) |
| Modulus of elasticity (Young’s modulus)                | E        | (MPa) |

2. From Pre-Process Conditions to Mechanical Characterization of FFF PLA

The systematic analysis of trends in the variation of the mechanical properties of PLA components as a function of one or more process parameters must take into consideration the values used for all factors that may influence these characteristics. Therefore, the operational conditions for all the steps involved, from filament production to mechanical testing, should be known.

In this connection, at least the following defining phases of the production and testing processes should be taken into account: (a) the manufacturing and storage conditions of the filament; (b) the design of the product and the selection of the infill parameters; (c) the selection of the process parameters; (d) type of the 3D printing equipment; (e) post-process treatments, storage conditions and ageing; and (f) the mechanical tests conditions.

2.1. The Manufacturing and Storage Conditions of the Filament

In fused filament fabrication processes, filaments with a circular cross-section and a diameter of 1.75 mm or 2.85 mm are used. Up to 17% variation of the ultimate tensile strength of specimens was pointed out in [18], using PLA filaments from different manufacturers. Significant differences (approximately 18% of the ultimate flexural strength) were also obtained by the bending test [19]. These differences may occur due to the manufacturing conditions or to the filament storage conditions. For example, the humidity of the filament storage enclosure can cause changes in the printing behavior and thereby noticeable variations of the mechanical properties. The color of the filament can also influence the mechanical characteristics of PLA specimens [20,21].
2.2. The Design of the Model and the Selection of the Infill Parameters

In the design process, the shape and dimensions of the part are determined. For 3D-printing fabrication, the output of the design must be a 3D model of the part, exported as a stl file. The quality of the stl file can influence the dimensional accuracy of the part. As the surfaces of CAD models are converted into meshes of triangles in stl files, an increase in the number of triangles leads to better quality, but also to an increase in stl file size.

The designer has also to define the infill settings that will be used. The selection of the infill pattern and density must be correlated with the stress and strain states for the future product. Both parameters are major factors of influence on the mechanical properties of 3D FFF-printed components [22–25]. The infill characteristics are to be set into the slicer software (addressed in the next step), but it is important to highlight that the infill selection is part of the design process of the component.

2.3. The Selection of the Process Parameters

This step involves the positioning of the part onto the printer’s build space, the choice of the values for the slicing parameters, and the setting of the temperature conditions. The G-code generated in the slicer software controls the printing process.

The selection of the process parameters must be correlated with the anisotropic behavior of PLA components manufactured by fused filament fabrication. Build orientation and raster settings have a major influence on the anisotropy of printed parts [26–29].

The designer must also consider at this stage the possibility of making the part with or without the use of support material. The use of support material can influence the surface quality and mechanical behavior of the products.

The high influence of the number of specimens printed simultaneously on the flexural strength of rectangular hollow cross-section specimens is highlighted in [30].

2.4. The Type of the 3D-Printing Equipment

The printing equipment can influence the dimensional accuracy and mechanical behavior of fused filament fabricated parts. Vettori and co-authors [8] present a round-robin study performed on PLA printed on different FFF equipment, using the same process parameters. The results show the important differences of the ultimate tensile strength values (max = 54.2 MPa, min = 13.2 MPa) depending on the printer used.

Temperature variations may occur in printing on open workspace equipment. Different mechanical properties can be achieved in these situations for identical components placed in different areas of the workspace. The use of closed space equipment with heat flow control can lead to optimized temperature distribution [31].

2.5. The Post-Process Treatments, Storage and Ageing

The mechanical behavior of FFF 3D-printed components can be influenced by post-printing thermal or thermo-chemical treatments, as well as by material ageing [32]. In [33] is highlighted the improvement of thermomechanical properties of PLA specimens subjected to post-print annealing. However, in [34] it is shown that PLA specimens obtained by FFF and annealed at 60–120 °C for 30–60 min showed a decrease in the modulus of elasticity and the ultimate tensile strength.

The properties of components made of PLA can be modified by the storage environmental conditions and the storage duration. Moreover, the dimensional accuracy of printed PLA components can be influenced by material volume changes and residual stress occurrence caused by the PLA crystallinity [35].

At low humidity, PLA has higher mechanical strength but lower toughness [36]. In [37] it is shown that reducing moisture content from 10% to 1% results in a decrease in the tensile strength with 24.4%.

In [38] are presented the variations of yield strength and modulus of elasticity as functions of the ageing time for printed PLA. An improvement of the mechanical characteristics
is observed with an increase in the ageing duration. Contrariwise, ageing for 240 h in a salt-fog environment causes a decrease of about 20% of the tensile strength [39].

2.6. The Mechanical Tests Conditions

The most commonly used testing methods for the characterization of the mechanical behavior of fused filament fabricated PLA parts are tensile tests and three-point bending tests [40]. At the moment, there are no specific ISO or ASTM standards defining the shape of specimens manufactured by FFF additive manufacturing. Thus, for the tensile tests “dog-bone” specimens defined by the general standards for plastics are used: ASTM D638-14 [41] and ISO 527-2:2012 [42]. The specimens used for the bending tests are defined by: ASTM D790-10 [43] and ISO 178:2019 [44].

The use of specimens with different shapes and dimensions may result in different mechanical characteristics. In [28], the authors estimate that the UTS values obtained by tests made on ASTM D638—Type IV specimens may be overestimated compared to the values resulting from tests performed on ASTM D638—Type I specimens.

One of the main problems highlighted in several papers refers to the occurrence of the breakage outside the gauge length of the tensile specimens. This improper failure may be related to the geometry of the dog-bone specimen, which leads to stress concentrations in the radius area [1]. Sierra et al. [45] studied the tensile behavior of ASTM D638 specimens with modified radius and conclude that the radius influences the mechanical strength obtained in tests. In [1] it is shown that an alternative to specimens with radius is the use of prismatic specimens defined by ISO 527-5 [46] and ASTM D3039 [47].

Valean et al. show that increasing the thickness of the specimen decreases the values of the mechanical characteristics UTS and E determined by tensile tests [48].

The variation of the mechanical properties of PLA specimens depending on the tensile test speed and the tensile test strain rate was analyzed in [49,50]. Vidakis and coauthors conclude that the tensile strength of PLA is strongly influenced by the strain rate and tensile test speed. The increase in the test speed from 10 mm/min to 100 mm/min leads to an increase in the tensile strength values by approximately 11% [50].

3. Layer Thickness

The layer thickness (or layer height) is the height of each deposited layer (Figure 1). For the top and the bottom layer, respectively, a distinct thickness can be set. It should be noted that the layer thickness is correlated with the diameter of the nozzle and the width of the raster.

![Figure 1. Layer thickness (t) for ISO 527-2 Type 1A tensile test specimens (S1, S2).](image)

In the research analyzed in this paper, the layer thickness was varied in the range of 0.06–0.6 mm, with the most commonly analyzed values situated between 0.10 mm and 0.30 mm. Selecting higher values for layer thickness leads to shorter production times, but also to lower part resolution. On the other hand, working with lower layer thicknesses determines longer durations of the printing processes and higher part resolution. The total number of layers is the ratio of the part height on the z-axis to the layer thickness (reference
system for upward building, according to ISO/ASTM 52921:2013). A 50% decrease in the layer thickness results in a doubling of the printing time. Increasing the number of layers emphasizes the re-heat effect for deposited layers, leading to improved diffusion and adhesion between layers.

It should be noted that the variation of the mechanical properties with the layer thickness is influenced also by other parameters (Table 2). For example, in [51] it is shown that the dependence of the tensile strength on the layer thickness is affected by the raster angle. On the other hand, the influence of the nozzle diameter of the printing head is greater than the influence of the layer thickness when a high yield strength is desired for a product [52]. Triyono et al. [53] indicate that the increase in the nozzle diameter leads to an increase in the density and the tensile strength of 3D-printed products. The authors consider that these two interconnected effects can be attributed to better interfacial bonding between the in-plane raster lines. At the same ratio between layer thickness and nozzle diameter, the adhesion between adjacent lines improves with the increases in the nozzle diameter. For big nozzle diameters, the raster lines were discovered to be even slightly overlapped.

Table 2. The influence of the layer thickness on the mechanical properties of FFF-printed PLA.

| Ref. | t (mm) | \( s_p \) (mm/s) | \( T_{H} \) (°C) | \( T_s \) (°C) | B.O. | \( \theta \) (°) | \( W \) (mm) | \( d_f \) (mm) | \( d_n \) (mm) | Nozzle Diameter | Build Plate Temperature | Filament Diameter | F.F.F. Process Parameters | Mechanical Test Settings | Results and Conclusions |
|------|--------|-----------------|----------------|----------------|------|----------------|-----------|-------------|-------------|------------------|---------------------|------------------|-----------------------|----------------------|------------------------|
| [19] | 0.06–0.60 | 25 | - | - | Vertical | - | \( d_i = 2.85 \) mm; \( d_o = 0.4–0.8 \) mm | Bending; rectangular hollow cross-section; \( s_l = 10 \) mm/min | UFS increases with the increase in the \( d_{i}/t \) ratio. UFS for t = 0.06, \( d_o = 0.4 \) mm, \( \theta = 90 \) ° is higher than UFS for t = 0.4, \( d_o = 0.4 \) mm. |
| [23] | 0.10–0.20 | 20–40 | 210 | - | XY | 45°/–45° | \( d_i = 1.75 \) mm; \( d_o = 0.4 \) mm; 20–80% infill | Tensile—ASTM D638 | Low increase in UTS with the decrease in layer thickness. |
| [24] | 0.10–0.30 | 30 | 195 | 110 | Horizontal | 40°–80° | \( d_i = 1.75 \) mm; \( d_o = 0.3 \) mm; 20–80% infill | Tensile—ASTM D638 | The variation of UTS vs. layer thickness is influenced by the raster angle. |
| [26] | 0.06–0.24 | 20–80 | 210 | - | YX; ZY | 0° | \( d_i = 1.75 \) mm; \( d_o = 0.4 \) mm; 100% infill | Tensile—ASTM D638; Bending—ASTM D790 | Highest UTS (89.1 MPa) for t = 0.06, \( s_p = 50 \) mm/s, XY specimens. Highest UFS (65 MPa) for t = 0.06, \( s_p = 80 \) mm/s, YZ specimens. |
| [28] | 0.06–0.50 | 30–200 | 175–230 | - | XY; ZX | - | \( d_i = 1.75 \) mm; \( d_o = 0.5 \) mm; 100% infill | Tensile—ASTM D638, Type I vs. Type IV | UTS decreases with the increase in the layer thickness. |
| [32] | 0.10–0.30 | 60 | 215 | 60 | Horizontal | 45°/–45°; 0°/90°; 0°/30°/60°/90°/60°/90° | \( d_i = 1.75 \) mm; 100% infill, aging; heat treatment | Tensile—ASTM D638 | Higher UTS for specimens with t = 0.1 mm. The decrease in UTS for t = 0.3 mm vs. t = 0.1 mm is higher for aged specimens, with and without heat treatment. |
| [51] | 0.06–0.35 | 60 | 190–220 | 60 | XY | 0°/90°; 45°/–45° | \( d_i = 1.75 \) mm; \( d_o = 0.4 \) mm; 100% infill; \( W_t = 2 \) | Tensile—ASTM D638, Type I specimens; \( s_l = 5 \) mm/min | The variation of UTS with layer thickness is influenced by \( \theta \). For \( \theta = 0 \)° the highest UTS is obtained for t = 0.06 mm. High variation of UTS vs. t for \( \theta = 90 \)°. |
| [54] | 0.10–0.40 | 90 | 185 | - | Z | - | \( d_i = 1.75 \) mm; 100% infill | Tensile—ASTM D638 IV; \( s_l = 5 \) mm/min | Highest UTS and E for t = 0.4 mm. |
| [55] | 0.20–0.40 | 50 | 190–210 | - | Horizontal | - | \( d_i = 2.85 \) mm; 20–100% infill; \( W_t = 2 \) | Tensile—ASTM D638, increased specimen thickness; \( s_l = 5 \) mm/min | Highest UTS (61.66 MPa) and E (3815.50 MPa) for t = 0.3 mm. |
Table 2. Cont.

| Ref. | \( t \) (mm) | \( \varphi_p \) (mm/s) | \( T_H \) \( ^\circ \text{C} \) | \( T_S \) \( ^\circ \text{C} \) | \( \beta_0 \) (\( \varnothing \)) | D (\( \varnothing \)) | Other Parameters | Mechanical Test Settings | Results and Conclusions |
|------|---------------|-------------------|------------------|------------------|-----------------|-----------------|------------------|------------------|------------------|
| [56] | 0.10–0.40     | 50–150            | 190–205          | -                | Horizontal      | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; } \) cooling fan | Tensile; \( s_k = 5 \text{ mm/min} \) | Highest UTS (60.26 MPa) for \( t = 0.10 \text{ mm; layer thickness was the dominant factor for UTS.} \) |
| [57] | 0.10–0.30     | 50                | 210              | 60 \( \alpha_{XY} = 0^\circ–60^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; } 20\text{-}80\% \text{ infill; } W_1 = 2 \) | Tensile—ASTM D638; Bending—ASTM D790; \( s_k = 1 \text{ mm/min} \) | Higher UTS obtained for \( t = 0.2 \text{ mm and } \alpha_{XY} = 30^\circ \text{ at } 80\% \text{ infill density; } \) Highest UFS obtained for \( t = 0.3 \text{ mm and } \alpha_{XY} = 0^\circ \text{ at } 80\% \text{ infill density.} \) |
| [58] | 0.125–0.25    | -                 | 210              | 60 \( \alpha_{XY} = 0^\circ ; \alpha_{YZ} = 45^\circ \) | -               | 50–90\% infill | Tensile—ISO 527 | Higher UTS for \( t = 0.25 \text{ mm.} \) |
| [59] | 0.10–0.35     | 40–80             | 220              | 25 \( \alpha_{XY} = 0^\circ–90^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } 100\% \text{ infill; variable cooling} \) | Tensile—ASTM D638, Type V specimens | Higher UTS for low values of the layer thickness. |
| [60] | 0.05–0.40     | 60                | 200              | -                | Horizontal; Vertical | -               | \( d_1 = 1.75 \text{ mm; } 60\% \text{ infill; variable cooling} \) | Tensile | Highest UTS (53.62 MPa) at \( t = 0.2 \text{ mm, for horizontal printed specimens.} \) |
| [61] | 0.20–0.30     | 38–52             | 190              | 40 \( \varnothing = 0^\circ; 90^\circ \) | -               | \( d_0 = 0.40 \text{ mm; } 40\% \text{ infill} \) | Bending—ASTM D790; \( s_k = 12 \text{ mm/min} \) | Higher flexural strength for \( t = 0.2 \text{ mm.} \) |
| [62] | 0.10–0.30     | 25–75             | 210              | 60 Vertical | -               | \( d_0 = 0.40 \text{ mm; four FFF printers (P1-P4)} \) | Bending, rectangular hollow cross-section; \( s_k = 10 \text{ mm/min} \) | PI-P2: UTS and sample mass decrease with thickness, P3-P4: maximum UFS for \( t = 0.15 \text{ mm and } t = 0.20 \text{ mm.} \) |
| [63] | 0.10–0.20     | 60                | 205              | 60 Horizontal \( 0^\circ; 18^\circ; 45^\circ; 72^\circ; 90^\circ \) | 100 infill; \( W_L = 2–6 \) | -               | Tensile—ASTM D638 modified specimens | Low variation of UTS and E with t. Highest UTS (49.29 MPa) and E (3497 MPa) for \( t = 0.10 \text{ mm.} \) |
| [64] | 0.10–0.30     | -                 | 210              | 80 \( \gamma_{XY} = 0^\circ–90^\circ \) \( 30^\circ; 45^\circ; 60^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } 50\% \text{ infill} \) | Tensile—ASTM D638 | UTS decreases with the increase in the layer thickness. |
| [65] | 0.10–0.30     | 30–90             | 210–230          | 50–80 XY, XZ \( \varnothing = 0^\circ/90^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; } 100\% \text{ infill; } W_1 = 2 \) | Tensile—ISO 527; \( s_k = 50 \text{ mm/min} \) | Higher UTS for \( t = 0.2 \text{ mm.} \) |
| [66] | 0.10–0.20     | 40–80             | 220              | 60 XY, XZ | -               | \( d_0 = 0.4 \text{ mm; } 100\% \text{ infill; } W_1 = 3 \) | Tensile—ISO 527; \( s_k = 5 \text{ mm/min} \) | Higher UTS (46.22 MPa) for XZ specimens with \( t = 0.1 \text{ mm, } s_k = 80 \text{ mm/s.} \) |
| [67] | 0.10–0.20     | 60                | 200              | 60 Horizontal | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; } 50\text{-}100\% \text{ infill} \) | Tensile—ISO 527 | Low variation of UTS and E with the layer thickness. Higher UTS for \( t = 0.1 \text{ mm.} \) |
| [68] | 0.10–0.40     | 60                | 230              | 80 Horizontal | -               | \( d_1 = 1.75 \text{ mm; } 100\% \text{ infill} \) | Tensile—ASTM D638; Bending—ASTM D790; Impact—ISO 180 | UTS, UFS and Izod impact strength decrease with the increase in layer thickness for all raster patterns. |
| [69–71] | 0.10–0.30 | 50                | 210              | 70 \( \varnothing = 0^\circ; 45^\circ; 90^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; } 100\% \text{ infill; } W_1 = 1 \) | Tensile—ASTM D638; Bending—ASTM D790; Impact—ASTM D256 | UTS and UFS decrease with the increase in the layer thickness. Izod impact strength increases with the layer thickness. |
| [72] | 0.10–0.20     | 30                | 200              | 50 XY, XZ, ZX \( 45^\circ/45^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm; 20}\text{-}50\% \text{ infill} \) | Tensile—ASTM D638; \( s_k = 5 \text{ mm/min} \) | Approx. 10.6% higher UTS for \( t = 0.10 \text{ mm compared to } t = 0.20 \text{ mm.} \) |
| [73] | 0.10–0.30     | 20                | 210              | 50              | -               | \( d_1 = 1.75 \text{ mm; } s_k = 1 \text{ mm/min} \) | Tensile, \( s_k = 1 \text{ mm/min} \) | Higher UTS (61.5 MPa) for \( t = 0.30 \text{ mm.} \) |
| [74] | 0.05–0.20     | 60                | 195–230          | 60 \( \bar{V}_p = 0^\circ–90^\circ \) | -               | \( d_1 = 1.75 \text{ mm; } d_n = 0.4 \text{ mm} \) | Tensile—ISO 527–2; \( s_k = 2 \text{ mm/min} \) | Low decrease for UTS with the increase in the layer thickness. |
Table 2. Cont.

| Ref. | t (mm) | \( s_p \) (mm/s) | \( T_H \) (°C) | \( T_S \) (°C) | B.O. (°) | Other Parameters | Mechanical Test Settings | Results and Conclusions |
|------|--------|------------------|----------------|----------------|------------|-----------------|-------------------------|--------------------------|
| [75] | 0.10-0.20 | 80 | 200 | 60 | XY | 45° | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.10 \text{ mm}; \) | Tensile—ASTM D638, Type IV | Highest UTS (40.07 MPa) for \( t = 0.15 \text{ mm}. \) |
| [76,77] | 0.10-0.30 | 60 | 215 | - | \( \gamma_{xy} = 0°-90° \) | - | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) | Tensile—ISO 527-2; \( \theta_s = 0.1 \text{ mm/min}; \) | Highest UTS for \( t = 0.10 \text{ mm}. \) Low variation of UTS and E with layer thickness. |
| [78] | 0.10-0.60 | - | - | - | \( \gamma_{yz} = 0°-90° \) | - | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) | Tensile—ISO 527-2; \( \theta_s = 0.1 \text{ mm/min}; \) | Low variation of UTS with layer thickness. |
| [79] | 0.10-0.30 | - | 220 | 60 | \( \gamma_{yz} = 0°-90° \) | - | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) | Tensile—ISO 527-2; | Highest UTS for \( t = 0.10 \text{ mm} \) and \( t = 0.20 \text{ mm}. \) Low variation of UTS vs. \( t. \) |

4. Printing Speed

The printing speed (mm/s) is the speed of the printing head in the XY plane during the deposition of the layers. This parameter is correlated with the flow rate (mm³/s).

In the research analyzed in this paper (Table 3) the printing speed was varied in the range of 20 mm/s–170 mm/s. The increase in the printing speed leads to a decrease in the part manufacturing duration but worsens the dimensional accuracy. High printing speeds reduce the degree of solidification of the bottom layers at the deposition of new layers. This can cause sliding processes between the successive deposited layers (mainly at the edges of the part) and thereby significant dimensional deviations.

Table 3. The influence of the printing speed on the mechanical properties of FFF-printed PLA.

| Ref. | \( s_p \) (mm/s) | t (mm) | \( T_H \) (°C) | \( T_S \) (°C) | B.O. (°) | Other Parameters | Mechanical Test Settings | Results and Conclusions |
|------|------------------|--------|----------------|----------------|------------|-----------------|-------------------------|--------------------------|
| [23] | 20–40 | 0.10-0.20 | 210 | - | XY | 45° | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) \( 20-90\text{° infill}; \) | Tensile—ASTM D638; | Low increase in UTS with the decrease in printing speed. |
| [26] | 20–80 | 0.06-0.24 | 210 | - | XY; YZ; ZY | 0° | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) \( 100\text{° infill}; \) | Tensile—ASTM D638; Bending—ASTM D790; | The variation of UTS vs. \( \theta_s \) is influenced by the build orientation and the layer thickness. |
| [29] | 20–80 | 0.40 | 215 | 55 | Horizontal | \( 0°; 30°; 45°; 60°; 90° \) | 100% infill; \( W_1 = 2 \) | Tensile—ASTM D638; \( \theta_s = 5 \text{ mm/min}; \) | Higher E and UTS values for \( s_p = 20 \text{ mm/s}. \) |
| [30] | 12.5–50 | 0.30 | 190–250 | 60 | Vertical | - | \( d_i = 2.8 \text{ mm}; \) \( d_o = 0.6 \text{ mm}; \) \( \text{variable cooling} \) | Bending, rectangular hollow cross-section; \( \theta_s = 10 \text{ mm/min}; \) | For \( T_H = 210 \text{°C} \) highest UTS (63.5 MPa) at \( s_p = 25 \text{ mm/s}; \) high influence of \( s_p \) on the specimen mass. |
| [54] | 70–170 | 0.30 | 185 | - | Z | - | \( d_i = 1.75 \text{ mm}; \) \( 100\text{° infill}; \) | Tensile—ASTM D638 IV; \( \theta_s = 5 \text{ mm/min}; \) | Low variations of UTS and E with printing speed. |
| [56] | 50–150 | 0.10-0.40 | 190–205 | - | - | - | \( d_i = 1.75 \text{ mm}; \) \( d_o = 0.4 \text{ mm}; \) | Tensile; \( \theta_s = 5 \text{ mm/min}; \) | Higher UTS for \( s_p = 80 \text{ mm/s} \) and \( s_p = 100 \text{ mm/s}. \) |
| [59] | 40–80 | 0.10-0.35 | 220 | 25 | \( \alpha_{xy} = 0°-90° \) | - | \( d_i = 1.75 \text{ mm}; \) \( 100\text{° infill}; \) | Tensile—ASTM D638 Type V specimens; \( \theta_s = 12 \text{ mm/min}; \) | Higher E and UTS values for low printing speed. |
| [61] | 38–52 | 0.20-0.30 | 190 | 40 | - | \( 0°; 90° \) | \( d_o = 0.4 \text{ mm}; \) \( 40\text{° infill}; \) | Bending—ASTM D790; \( \theta_s = 12 \text{ mm/min}; \) | Higher flexural strength for \( s_p = 28 \text{ mm/s}. \) |
| [62] | 25–75 | 0.10-0.30 | 210 | 60 | Vertical | - | \( d_o = 0.4 \text{ mm}; \) \( 4 \text{ FFF printers} \) | Bending, rectangular hollow cross-section; \( \theta_s = 5 \text{ mm/min}; \) | Higher UTS for \( s_p = 25 \text{ mm/s}. \) |
Table 3. Cont.

| Ref. |  | FFF Process Parameters | Mechanical Test Settings | Results and Conclusions |
|------|------------------|------------------------|--------------------------|-------------------------|
|      | ρp (mm/s)        | T_h (°C) | T_B (°C) | B.O. (°) | θ (°) | Other Parameters |                               |
| [65] | 30–90            | 0.10–0.30 | 210–230 | 50–80 | XY | 0° /90° | d_1 = 1.75 mm; d_2 = 0.4 mm; W_l = 2 | Tensile—ISO 527-2; s_p = 50 mm/min | Low decrease in UTS with the increase in the printing speed. |
| [73] | 20–60            | 0.20 | 210 | 50 | - | - | d_1 = 1.75 mm | Tensile; s_p = 1 mm/min | Higher UTS for s_p = 20 mm/s. |
| [80] | 40–50            | 0.20 | 190–230 | 50 | XY | 45° | d_1 = 1.75 mm; d_2 = 0.4 mm; 100% infill | Tensile—ASTM D638 Type IV specimens | Higher UTS values for s_p = 50 mm/s (except the T_h = 230°C specimens). |
| [81] | 50–150           | - | 190–210 | Horizontal | - | 20–100% infill | Tensile—ASTM D638 Type V specimens | Highest UTS (45.27 MPa) obtained for s_p = 100 mm/s and T_h = 210°C. |
| [82] | 60–100           | 0.10–0.30 | - | - | Horizontal | - | 60–100% infill | Tensile—ASTM D638; Bending—ASTM D6390 | Infill density and printing speed have the highest influence on UFS and UTS. |
| [83] | 20–60            | 0.08–0.28 | 210–220 | - | XY, XZ | 0° /90°; 30° /–60°; 45° /–45° | d_1 = 0.3–0.5 mm; d_2 = 0.4 mm; 100% infill; W_l = 2| Tensile—ASTM D638; Compression—ASTM D3410; s_p = 5 mm/min | Higher UTS for s_p = 20 mm/s. The optimum parameters for UTS: s_p = 20 mm/s, T_h = 220°C, XZ orientation, 30° /–60° raster. |
| [84] | 40–140           | 0.10 | 210 | 50 | - | - | 100% infill; W_l = 2; variable flow rate | Tensile—GB/T 11997 type-A specimens; s_p = 5 mm/min | Low influence of the printing speed. High influence of the flow rate. |
| [85] | 35–45            | 0.20 | 180–220 | 25 | XY | 45° /–45° | d_1 = 1.75 mm; 20% infill | Tensile—ASTM D638; Bending—ASTM D6390; Compression—ASTM D3410; s_p = 5 mm/min | Tensile: higher UTS for s_p = 45 mm/s and s_p = 40 mm/s at T_h = 200–220°C; Bending: higher UTS for s_p = 45 mm/s; Compression: higher strength for s_p = 45 mm/s. |
| [86] | 35–65            | 0.10 | 200 | 60 | XY | 45° /–45°; 0° /90° | d_1 = 2.85 mm; 100% infill | Tensile—ASTM D638 | Decrease in UTS with the increase in the printing speed. |
| [87] | 50–100           | 0.10–0.20 | 210 | 60 | Vertical | - | 40–80% infill | Bending, circular hollow cross-section specimens | Higher UTS for low printing speed and low layer thickness. |
| [88] | 30–40            | - | 180–195 | - | - | 45° /–45°; 0° /90° | - | Tensile—ASTM D638; Compression—ASTM D3410; s_p = 5 mm/min; Bending—ASTM D6390; s_p = 2 mm/min | The optimum parameters for tensile test: s_p = 40 mm/s, T_h = 180°, θ = 30° /–60°; The optimum parameters for bending test: s_p = 30 mm/s, T_h = 185°, θ = 30° /–60°. |

5. Printing Head Temperature and Build Plate Temperature

The printing head temperature is one of the most studied process parameters. As revealed by Table 4, the researchers selected printing head temperatures ranging from 175 °C to 275 °C for manufacturing of the PLA samples, but the most commonly analyzed temperatures were situated between 190–220 °C. These values correlate with the melting point of PLA (160 °C up to 180 °C). The tendency to use lower temperatures is associated with the susceptibility of the PLA to thermal degradation at high temperatures and with economic issues (reduced energy consumption). At the same time, at low printing temperatures (below 180 °C, according to [34]), melting may not be complete and interlayer diffusion may not occur. Low diffusion between layers can cause delamination (peeling of layers). In [89] it is shown that at low printing temperatures the air gaps between raster lines are larger, which leads to reduced tensile strength.
Table 4. The influence of the head temperature and build plate temperature on the mechanical properties of FFF-printed PLA.

| Ref. | T<sub>h</sub> (°C) | T<sub>p</sub> (°C) | t (mm) | t<sub>h</sub> (mm/s) | B.O. | 0 (°) | Other Parameters | Mechanical Test | Results and Conclusions |
|------|-----------------|-----------------|--------|---------------------|------|-------|------------------|----------------|------------------------|
| [30] | 190–250         | 60              | 0.30   | 12.5–50             | Vertical | d<sub>h</sub> = 2.85 mm; d<sub>0</sub> = 0.6 mm; variable cooling | Bending, rectangular hollow cross-section; s<sub>h</sub> = 10 mm/min | Increase in ultimate flexural strength and specimen mass with the printing head temperature. |
| [33] | 190–230         | 45–105          | -      | 50                  | -     | d<sub>h</sub> = 2.85 mm; 100% infill | Tensile—ASTM D638; Bending—ASTM D790; Impact—ASTM D256 | Mechanical parameters increase with T<sub>h</sub>. The influence of T<sub>p</sub> is lower compared to the influence T<sub>h</sub>. |
| [34] | 180–240         | -               | 0.10   | 60                  | Horizontal | d<sub>h</sub> = 1.75 mm; annealing | Tensile—ISO5272; s<sub>h</sub> = 5 mm/min | Increase in UTS and E with T<sub>h</sub> for specimens without annealing. |
| [51] | 190–220         | 60              | 0.06–0.35 | 60 | XY | d<sub>h</sub> = 1.75 mm; d<sub>0</sub> = 0.4 mm; W<sub>h</sub> = 2 | Tensile—ASTM D638-4 specimens; s<sub>h</sub> = 5 mm/min | Highest UTS values for T<sub>h</sub> = 220 °C and T<sub>p</sub> = 205 °C. High variation of UTS vs. T<sub>h</sub> for 0–90°. |
| [54] | 175–205         | -               | 0.30   | 90                  | Z     | d<sub>h</sub> = 1.75 mm; 100% infill | Tensile—ASTM D638 Type IV; s<sub>h</sub> = 5 mm/min | Highest UTS (43.79 MPa) at T<sub>h</sub> = 205 °C. Approx. 35% increase in UTS for T<sub>p</sub> = 205 °C, compared to T<sub>p</sub> = 175 °C. |
| [55] | 190–210         | -               | 0.20–0.40 | 50 | Horizontal | d<sub>h</sub> = 2.85 mm; 20–100% infill; W<sub>h</sub> = 2 | Tensile—ASTM D638; increased specimen thickness; s<sub>h</sub> = 5 mm/min | Highest UTS for T<sub>h</sub> = 210 °C and T<sub>p</sub> = 200 °C. |
| [56] | 190–205         | -               | 0.10–0.40 | 50–150 | Horizontal | d<sub>h</sub> = 1.75 mm; d<sub>0</sub> = 0.4 mm; cooling fan | Tensile test; s<sub>h</sub> = 5 mm/min | Higher UTS obtained for T<sub>h</sub> = 210 °C and active cooling fan; higher T<sub>p</sub> recommended for high layer thickness. |
| [65] | 210–230         | 50–80           | 0.10–0.30 | 30–90 | XY | d<sub>h</sub> = 0.4 mm | Tensile—ISO 5272; s<sub>h</sub> = 50 mm/min | Low increase in UTS with the increase in T<sub>h</sub> and decrease in T<sub>p</sub>. |
| [71] | 200–230         | 50–70           | 0.20   | 20                  | -     | d<sub>h</sub> = 1.75 mm | Tensile; s<sub>h</sub> = 1 mm/min | Highest UTS (62 MPa) for T<sub>h</sub> = 220 °C. Low variation of UTS vs. T<sub>p</sub>. |
| [74] | 195–230         | 60              | 0.05–0.20 | 60 | β = 0°–90° | d<sub>h</sub> = 1.75 mm; d<sub>0</sub> = 0.4 mm | Tensile—ISO 5272; s<sub>h</sub> = 2 mm/min | Higher UTS for T<sub>h</sub> = 210–215 °C. |
| [80] | 190–230         | 50              | 0.20   | 40–50              | XY | d<sub>h</sub> = 1.75 mm; d<sub>0</sub> = 0.4 mm; W<sub>h</sub> = 3 | Tensile—ASTM D638 Type IV specimens | Approx. 20% increase in UTS for T<sub>h</sub> = 210 °C, compared to T<sub>p</sub> = 190 °C. |
| [81] | 190–210         | -               | 0.20 | 50–150             | Horizontal | d<sub>h</sub> = 20–100% infill | Tensile—ASTM D638 Type V specimens | Highest UTS (45.27 MPa) obtained for s<sub>h</sub> = 100 mm/s and T<sub>p</sub> = 210 °C. |
| [83] | 210–220         | -               | 0.08–0.28 | 20–60 | XY; XZ | d<sub>h</sub> = 0.3–0.5 mm; W<sub>h</sub> = 0–100% infill; W<sub>h</sub> = 2–4 | Tensile—ASTM D638; Bending—ASTM D790; Compression—ASTM D3410 | Higher UTS for T<sub>h</sub> = 220 °C. |
| [85] | 180–220         | 25              | 0.20   | 35–45              | XY | d<sub>h</sub> = 1.75 mm; d<sub>0</sub> = 0.4 mm; 20% infill | Tensile—ASTM D638; Bending—ASTM D790; Compression—ASTM D3410 | Higher UTS for T<sub>h</sub> = 220 °C; Higher compressive strength for T<sub>h</sub> = 190–220 °C; Higher bending strength for T<sub>h</sub> = 190–210 °C. |
Higher printing head temperatures can provide better interlayer diffusion and higher mechanical properties, but also a slip of the deposited material, affecting the dimensional accuracy of the components. In [34] it is shown that the use of printing temperatures above 240 °C causes an unsteady flow of material from the printing head nozzle.

The build plate temperature is generally set in the range of 50–60 °C. In open-space 3D printers, the uniformity of the build plate temperature is difficult to achieve because of the heat flows. In general, in the central areas of the build plate the temperature is higher compared to the peripheral areas. This disadvantage is mitigated for the printers by closed work space and controlled heat flow. In [60] it is shown that the influence of the heat flux on the ultimate tensile strength is low when the specimens are printed horizontally and high when the specimens are printed vertically.

Considering both temperature-related parameters—the printing head temperature and the build plate temperature, respectively—it is shown that the influence of the printing head temperature on the mechanical properties is lower compared to the influence of the build plate temperature [33].

The importance of temperature profile monitoring during the FFF-printing process by using specific devices (infrared camera, thermocouples) and the development of numerical heat transfer models is highlighted in [96].

### 6. Build Orientation of the Specimens

The placement of the 3D model onto the building space of the printer is one of the main factors that determine the anisotropic behavior of PLA FFF-printed parts. In this regard, high differences were found between the mechanical behavior along the x and y axes (axes situated in the plane of the build plate—Figure 2) and the mechanical behavior along the vertical z-axis. Variations of mechanical properties for the parts rotated with various angles to the reference system must also be included in the analysis.

| Ref. | T<sub>H</sub> (°C) | T<sub>B</sub> (°C) | l (mm) | t<sub>y</sub> (mm/s) | B.O. (°) | θ (°) | Other Parameters | Mechanical Test Settings | Results and Conclusions |
|------|------------------|------------------|--------|------------------|--------|------|------------------|--------------------------|-------------------------|
| [90] | 190–210          | 55               | 0.35   | 40               | Horizontal 0°; 45°; 90° | d<sub>i</sub> = 2.85 mm; d<sub>i</sub> = 0.4 mm; W<sub>1</sub> = 2 | Tensile—ASTM D638-10-I; s = 5 mm/min | Higher UTS and E for T<sub>H</sub> = 210 °C (for all raster). Highest UTS (56.2 MPa) for specimens with T<sub>H</sub> = 210 °C and θ = 0°. |
| [91] | 180–210          | 60               | 0.20   | 50               | XY 45/−45° | d<sub>i</sub> = 0.4 mm; 100% infill; 70–160% flow | Tensile—ISO 527–2 | The variation of tensile load vs. temperature is influenced by the flow rate. |
| [92] | 210              | 40–80            | 0.20   | -                | Horizontal 45/−45° | d<sub>i</sub> = 1.75 mm; d<sub>i</sub> = 0.4 mm | Tensile—ASTM D638 Type IV specimens | Higher strength for specimens printed inside of a heated chamber. |
| [93] | 195–255          | 55               | 0.30   | 45               | XY 0° | d<sub>i</sub> = 1.75 mm; d<sub>i</sub> = 0.5 mm; 100% infill; annealing | Tensile—ISO 527; Bending—EN ISO 178:2011 | Higher UTS and UFS for T<sub>H</sub> = 235–255°C. |
| [94] | 180–230          | 70–110           | 0.30   | 40               | YZ 0°/90° | d<sub>i</sub> = 1.75 mm; d<sub>i</sub> = 0.4 mm; 99% infill | Tensile—ASTM D368 Type IV specimens | Highest UTS (76.5 MPa) for T<sub>H</sub> = 200 °C and T<sub>B</sub> = 70 °C. Lowest UTS (69 MPa) for T<sub>H</sub> = 180 °C and T<sub>B</sub> = 110 °C. |
| [95] | 210–230          | 70               | 0.20   | 40               | XY 45/−45° | d<sub>i</sub> = 1.75 mm; 100% infill | Tensile—ASTM D368 Type IV specimens; s = 1 mm/min | Highest UTS (53 MPa) and E (2.5 GPa) for T<sub>H</sub> = 220 °C. Lowest UTS (47 MPa) and E (2.2 GPa) for T<sub>H</sub> = 230 °C. |
In the ISO/ASTM 52921:2013 standard [17] the notation of the orthogonal orientation (non-rotated) of a prismatic part relative to the printer reference system is done by combinations of three letters: the first letter of the notation represents the axis parallel to the longest characteristic dimension of the part, the second letter represents the axis parallel to the second-longest characteristic dimension of the part and the third letter represents the axis parallel to the third characteristic dimension. If the part has a symmetry plane (as in the case of dog-bone tensile specimens), a simplified notation consisting of the first two letters may be used.

Figure 2 shows the notation of the positioning of an ISO 527–2:2012 Type 1A tensile specimen. The first characteristic dimension is the length of the specimen and the second characteristic dimension is the width of the specimen. The necessity of using standardized notations for build orientation results from the analysis of the articles published so far (Table 5). In several articles, XY and YX build orientations are referred to as “flat build orientations”, XZ and YZ build orientations are referred to as “on-edge build orientations” and ZX and ZY build orientations are referred to as “upright build orientations”. The use of the term “flat build orientation”, without graphic detail, does not clearly indicate whether XY or YX build orientation is used. The ambiguity is amplified in the cases where rotated specimens relative to the orthogonal orientation are used. In this paper we propose the use of angles $\alpha$, $\beta$ and $\gamma$ for describing rotations in the $xy$, $yz$ and $zx$ planes. To define the angle of rotation relative to an orthogonal orientation, indices will be used (angle $\alpha_{XZ}$ defines a specimen rotated by $\alpha^\circ$ in the $xy$ plane relative to the base orientation XZ, angle $\alpha_{XZ} = 0^\circ$ represents the XZ orthogonal orientation and $\alpha_{XZ} = 90^\circ$ represents the YZ orientation). For a comparative analysis, the notations from Figure 2 were used for the papers listed in Table 5. For some papers, where it was not possible to unambiguously identify the build orientation, the notations given by the authors were maintained.
Table 5. The influence of the build orientation and the printing orientation angle on the mechanical properties of FFF-printed PLA.

| Ref. | B.O. | 1  | t_p  | T_h  | T_c  | d_i  | d_o  | d_n  | W_i  | Other Parameters | Mechanical Test Settings | Results and Conclusions |
|------|------|----|------|------|------|------|------|------|------|------------------|--------------------------|--------------------------|
| [26] | YX; YZ; ZX | 0.06–0.24 | 20–80 | 210 | - | 0° | d_i = 1.75 mm; d_o = 0.4 mm; 100% infill | Tensile—ASTM D638; Bending—ASTM D790 | High variation of UTS and UFS. Highest values for XY and YZ specimens. |
| [27] | XY; XZ; ZX | 0.20 | - | - | 45° / -45° | 50–100% infill | d_i = 1.75 mm; d_o = 0.5 mm; 100% infill; variable flow | Tensile—ISO 527–2; s_i = 10 mm/min | Highest UTS (56.5 MPa) for flat XY specimens at 100% infill. 13% and 37% decrease in UTS for XZ and ZX specimens. |
| [28] | XY; ZX | 0.06–0.50 | 30–200 | 175–230 | - | - | d_i = 1.75 mm; d_o = 0.4 mm; 20% infill | Tensile—ASTM D638 Type I vs. Type IV | UTS for ZX specimens is 47.9% lower compared to UTS for XY specimens. |
| [54] | X; Y; Z | 0.30 | 90 | 185 | - | - | d_i = 1.75 mm; 100% infill | Tensile—ASTM D638 IV; s_i = 5 mm/min | Low variation of UTS with build orientation. |
| [60] | Horizontal, vertical | 0.05–0.40 | 60 | 200 | - | - | d_i = 1.75 mm; 60% infill | Tensile | UTs for vertical specimens 50% lower than UTs for horizontal specimens. |
| [73] | XY; XZ; ZX | 0.10 | 30 | 200 | 50 | 45° / -45° | d_i = 1.75 mm; d_o = 0.4 mm; 20% infill | Tensile—ASTM D638; s_i = 5 mm/min | Higher UTs (38.47 MPa) for XY specimens compared to XZ (30.10 MPa) and ZX (27.63 MPa) specimens. |
| [83] | XY; XZ | 0.08–0.28 | 20–60 | 210–220 | - | 0° / 90°; 30° / -30°; 45° / -45° | d_i = 0.3–0.5 mm; 80–100% infill; s_i = 5 mm/min; W_i = 2–4 | Tensile—ASTM D638-1; s_i = 5 mm/min | Higher UTs for XZ specimens. |
| [97] | XY; XZ; ZX | 0.40 | 3 | 220 | - | - | d_i = 0.4 mm; 100% infill | Tensile—ASTM D638 | Highest values of E and UTS for XZ specimens. |
| [98] | XY; XZ; ZX | 0.20 | 60 | 210 | 45 | 45° / -45° | d_i = 1.75 mm; d_o = 0.4 mm; W_i = 2 | Tensile—ASTM D638 Type I specimens | Highest values of UTs (57.58 MPa) and E (2571 MPa) for XY specimens. Low value of UTs (23.75 MPa) for XZ specimens. |
| [99] | XY; XZ; ZX | 0.18 | 80 | - | - | - | d_i = 1.75 mm; 20–100% infill | Tensile—ASTM D638; s_i = 5 mm/min | Higher UTs (34.45–35.47 MPa) for XZ specimens. Low UTs for XY and XZ specimens. The variations are influenced by the raster. |
| [100] | XY; XZ; ZX | 0.20 | 50 | 215 | 60 | 0°; 45°; 90° | d_i = 1.75 mm; d_o = 0.4 mm; 100% infill; W_i = 2 | Tensile—ASTM D638; s_i = 5 mm/min | Higher UTs (56.5 MPa) compared to XY specimens 50% lower. |
| [57] | α_{XY} = 0° / 60° | 0.10–0.30 | 50 | 210 | 60 | - | d_i = 1.75 mm; d_o = 0.4 mm; 20–80% infill; W_i = 2 | Bending—ASTM D790; Tensile—ASTM D638 | Low variation of the flexural strength and the tensile strength with α_{XY}. |
| [58] | α_{XY} = 0° / -45° | 0.125–0.25 | - | - | - | - | 50–90% infill | Tensile—ISO 527–1.2 | Low variation of UTs vs. the α_{XY} angle. |
| [59] | α_{XY} = 0° / -90° | 0.10–0.35 | 40–80 | 220 | 25 | - | d_i = 1.75 mm; 100% infill | Tensile—ASTM D638; Type V | Higher E and UTs for α_{XY} = 0° and α_{XY} = 45°. |
| [64] | γ_{XY} = 0° / -90° | 0.10–0.30 | - | 210 | 80 | 30°; 45°; 60° | d_i = 1.75 mm; 50% infill | Tensile—ASTM D638 | Highest UTs for γ_{XY} = 0° and γ_{XY} = 45° specimens. |
| [74] | β_{YZ} = 0° / -90° | 0.05–0.20 | 60 | 195–230 | 60 | - | d_i = 1.75 mm; d_o = 0.4 mm | Tensile—ISO 527–2; s_i = 2 mm/min | High decrease in UTs with the increase in β_{YZ}. |
Analyzing the data presented in Table 5, it can be concluded that the ZX- and ZY-type build orientations lead to much lower mechanical characteristics compared to the XY, YX, ZX and YZ layouts. This mechanical behavior is generated by the inter-layer breakage that occurs in ZX and ZY specimens.

At tilted specimens relative to the build plate (0° < β_{YX} < 90°; 0° < β_{YZ} < 90°; 0° < γ_{XZ} < 90°; 0° < γ_{XY} < 90°), the mechanical characteristics decrease with increases in the tilt angle.

A comparative analysis of the XY and the YX build orientations should be correlated with the raster angle (similar for specimens with 0° < α_{XY} < 90°).

The anisotropic character of components made by FFF printing was also evidenced by some authors through mechanical tests performed on specimens obtained by conventional machining (cutting) from 3D-printed prismatic blocks [105].

### Table 5. Cont.

| Ref.          | B.O. (-) | FFF Process Parameters | Mechanical Test Settings | Results and Conclusions |
|--------------|---------|------------------------|--------------------------|-------------------------|
| [76]         | γ_{XZ} = 0°–90° | 0.10–0.30 - 215 - - d_{l} = 1.75 mm | Tensile—ISO 527–2 | High variation of UTS with the γ_{XZ} angle, from 55.86 MPa (XZ specimens, γ_{XZ} = 0°) to 26.65 MPa (ZX specimens, γ_{XZ} = 90°). |
| [78]         | γ_{XZ} = 0°–90° | 0.10–0.60 - - - - d_{l} = 1.75 mm; da = 0.4 mm | Tensile—ISO 527–2; s = 0.1 mm/min | High variation of UTS with the γ_{XZ} angle, from 51.33 MPa (XZ specimens, γ_{XZ} = 0°) to 34.56 MPa (ZX specimens, γ_{XZ} = 90°). |
| [79]         | γ_{XZ} = 0°–90° | 0.10–0.30 - 220 60 - - d_{l} = 1.75 mm | Tensile—ISO 527–2 | High variation of UTS with the γ_{XZ} angle, from 49.66 MPa (XZ specimens, γ_{XZ} = 0°) to 23.40 MPa (ZX specimens, γ_{XZ} = 90°). |
| [101]        | α_{XY} = 0°–90°; β_{YX} = 0°–90°; γ_{XZ} = 0°–90° | 0.10 - - - - d_{a} = 0.4 mm; 99% infill | Tensile—ISO 527–2 | Highest UTS (55.68 MPa) for XZ (γ_{XZ} = 0°); Low UTS (23.68–15.5 MPa) for YX, YZ, β_{YX} = 45° and α_{XY} = 45° specimens. |
| [102]        | γ_{XY} = 0°–90°; γ_{XZ} = 0°–90° | 0.2 50 225 60 - d_{l} = 2.75 mm; da = 0.6 mm | Tensile—ISO 527; Bending—ISO 178; Compression—ISO 604 | Highest UTS (49.8 MPa) for XZ (γ_{XZ} = 0°). Lowest UTS (21.5 MPa) for ZY and ZX. UTS decreases with the increase in γ_{XY} and γ_{XZ}. Low variation of the compressive strength. |
| [103]        | γ_{XY} = 0°–90°; γ_{XZ} = 0°–90° | 0.15 60 220 60 - d_{l} = 1.75 mm; da = 0.4 mm; 25–100% infill | Tensile—ASTM D638; Shear—ASTM D5379 | High decrease in UTS with the increase in Y_{XZ}; UTS = 55 MPa for XZ (γ_{XZ} = 0°). Highest shear strength (36 MPa) for γ_{XY} = 45°. |
| [104]        | β_{YX} = 0°–90°; β_{XY} = 0°–90°; β_{YZ} = 0°–90° | 0.20 35 205 60 0°/90°; 30°/–60°; 45°/–45°; 60°/–30°; 90°/0° d_{l} = 1.75 mm; da = 0.4 mm; 10% infill | Tensile—ASTM D638 | Low influence of β_{YX}; High influence of β_{XY} and β_{YZ}. Highest UTS (27.6 MPa–30.9 MPa) for β_{YX} = 0°–90°, β_{XY} = 0° and β_{YZ} = 0° specimens. |

**7. Raster Angle**

The raster of the 3D-printed parts represents the arrangement of the successive lines of a layer (Figure 3). The mechanical behavior is influenced by several raster parameters: the raster angle, how the raster angle alternates between two successive layers, the width of a raster line, the distance between two successive raster lines, the number of wall lines and the distance between the raster and the wall lines [106].
Figure 3. Raster angle ($\theta$).

The raster angle influences the anisotropic mechanical behavior and the breakage of 3D FFF-printed components. Two main types of layouts are distinguished: unidirectional raster (the same raster angle is maintained for all successive layers) and alternating raster (the raster angle varies between successive layers, usually by 90°). Even in the case of the raster angle, a standardization of notations is needed with a clear identification of the alternating raster. Therefore, notations in the form of $\theta_1^\circ / \theta_2^\circ$ could be used, where $\theta_1^\circ$ and $\theta_2^\circ$ represent the raster angles for two successive layers.

In the previous research were analyzed specimens with unidirectional raster and alternating raster (Table 6—the first 11 lines of the table show unidirectional raster, the next 14 lines of the table show alternating raster). The highest mechanical properties were obtained for the specimens with alternating raster. The analysis of the mechanical behavior as a function of the angle of the raster should be carried out correlated with the specimen build orientation.

| Ref. | $\theta$ ($^\circ$) | FFF Process Parameters | Mechanical Test Settings | Results and Conclusions |
|------|---------------------|------------------------|--------------------------|------------------------|
| [24] | 40°; 60°; 80°        | 0.10–0.30 30 195 110 Horizontal | $d_1 = 3.40$ mm; $d_2 = 1.80$ mm; 20–80% infill | The raster angle has a high significance on UTS. Maximum UTS (50.3 MPa) and $E$ (1890 MPa) obtained at $\theta = 0^\circ$ and 10% moisture content. |
| [25] | 0°; 45°; 90°        | 0.20 - - - X; Y; Z; Z; X | - | The variation of UTS vs. $\theta$ is influenced by the layer thickness. |
| [26] | 0°; 30°; 45°; 60°; 90° | 0.40 20–40 215 55 Horizontal | $d_1 = 2.85$ mm; $d_2 = 0.40$ mm; 100% infill | A decrease of 16.7 % of the UTS for $\theta = 90^\circ$ compared to $\theta = 0^\circ$ and $\theta = 45^\circ$ specimens. |
| [27] | 0°; 45°; 90°        | 0.10 30 240 60 Horizontal | $d_1 = 2.85$ mm; $d_2 = 0.40$ mm; 100% infill; $s_{\theta} = 12$ mm/min | For $t = 0.40$ mm all specimens fractured in the direction of the raster. Highest UTS for $\theta = 0^\circ$ specimens; UTS decreases by approx. 40% for $\theta = 90^\circ$ specimens. |
| [28] | 0°; 18°; 45°; 72°; 90° | 0.10–0.20 38–52 150 40 - | $d_1 = 0.40$ mm; 40% infill | A higher flexural strength for $\theta = 0^\circ$ specimens. |

Table 6. The influence of the raster angle on the mechanical properties of FFF-printed PLA.
| Ref. | θ¹ | FFF Parameters | Mechanical Test Settings | Results and Conclusions |
|------|-----|----------------|--------------------------|-------------------------|
| [64] | 30°; 45°; 60° | T = 0.10-0.30, y = 0-90° | Tensile—ASTM D638 | UTS decreases with the increase in θ. |
| [69–71] | 0°; 45°; 90° | T = 0.10-0.30, y = 0-90° | Tensile—ASTM D638, Bending—ASTM D790, Impact—ASTM D256 | High influence of the raster angle on the mechanical properties. Highest UTS, UFS and Izod impact strength for 0° = 0° specimens. |
| [90] | 0°; 45°; 90° | T = 0.35, y = 190–210, 55 | Horizontal | Tensile—ASTM D638-10-4, s5 = 5 mm/min | Highest UTS and E for 0° = 0° specimens. Lowest UTS and E for 0° = 90° specimens. |
| [107] | 0°; 30°; 45°; 60°; 90° | T = 0.20, y = 30–60 | Horizontal | Tensile—ISO 527-2, Type 1B specimens | Breaking surface aligned with the raster. Highest UTS and E for 0° = 0°; UTS decreases by approx. 70% for 0° = 90°. |
| [108] | 0°; 30°; 45°; 60°; 90° | T = 0.20, y = 70–200 | XY | Tensile—ASTM D638 | High influence of the raster angle on UTS. Highest UTS for 0° = 45°. |
| [27] | 0°; 45°; 45°; 45°; 0° | T = 0.20, y = 60 | XY, ZY, ZK | 50–100% infill | Tensile—ISO 527-2, s = 10 mm/min | Highest UTS (58.4 MPa) for 0° = 45°. |
| [32] | 45°–60°, 0°–30°, 30°–60°, 90° | T = 0.10-0.30, y = 60 | Horizontal | Tensile—ASTM D638 | Higher UTS for 0° = 45°–60°. The variation of UTS vs. raster angle is influenced by heat treatment and aging. |
| [33] | 0°; 90°; 15°/75°, 30°/60°, 45°/45° | T = 0.50, y = 190–230 | 45–105 | - | Tensile—ASTM D638, s = 5 mm/min; Bending—ASTM D790, Impact—ASTM D256 | Highest values of tensile strength, flexural strength and Izod impact strength obtained for 0° = 45°/45°. |
| [51] | 0°; 90°; 45°–60° | T = 0.06-0.35, y = 60 | XY | Tensile—ASTM D638-4 specimens, s = 5 mm/min | Tensile—ASTM D638; s = 5 mm/min | Highest UTS for 0° = 45°–60°. Low values of UTS for specimens with 0° = 90° and t = 0.06 mm. |
| [83] | 0°; 90°; 30°–60°, 45°–45° | T = 0.08–0.28, y = 20–60 | 210–220 | - | Tensile test, ASTM D638-1; s = 5 mm/min | Tensile—ASTM D638 | Higher UTS for specimens with 0° = 30°–60° and 0° = 45°–45°. |
| [86] | 45°–60°; 90° | T = 0.10, y = 35–65 | 200 | XY | Tensile—ASTM D638 | Higher UTS for 0° = 45°–60°. |
| [104] | 0°/90°; 30°–60°, 45°–45°; 90°/0° | T = 0.20, y = 35 | 205 | - | β1y = 0°–90°, β2y = 0°–90°, β1z = 0°–90°, β2z = 0°–90° | Tensile—ASTM D638, s = 5 mm/min | Low influence (2 MPa) of the raster angle on UTS, at 10% infill. |
| [107] | 0°/90°; 30°–60°, 45°–45° | T = 0.20, y = 30 | 200 | Horizontal | 100% infill | Tensile—ISO 527-2, Type 1B specimens | Low influence of the alternating raster angle on the elastic modulus and the ultimate tensile strength. |
| [109] | 0°/90°; 15°/75°, 30°–60°, 45°–45° | T = 0.20, y = 55 | 210 | Horizontal | - | Tensile—ASTM D638, s = 0.5 mm/min; fracture test | Tensile—ASTM D638; s = 0.5 mm/min | Highest UTS for 0° = 0°. Highest fracture load (865.1 N) in fracture test specimens with 0° = 45°–45°. |
| [110] | 0°/90°; 45°–45° | T = 0.30, y = 50 | 190 | XY | da = 0.4 mm | Tensile—ASTM D638; s = 5 mm/min | Highest UTS for 0° = 0°. Low influence of the raster angle on the elastic modulus for PLA. |
| [111] | 0°/90°; 45°–45° | T = 0.20, y = 120 | 200 | Horizontal | da = 1.75 mm, da = 0.4 mm, 30/90° infill, W1 = 2 | Tensile—ISO 527 | A higher strength of specimens for 0° = 45°–45°. Low influence of raster angle on elastic modulus. |
Table 6. Cont.

| Ref. | θ (°) | FFF Process Parameters | Mechanical Test Settings | Results and Conclusions |
|------|-------|------------------------|--------------------------|-------------------------|
|      |       | t (mm) | s_p (mm/s) | T_H (°C) | T_B (°C) | B.O. | Other Parameters |                           |                          |
| [112]| 0°; 90°; 45°/0°/90°/135° | 0.14 | 40 | 215 | 60 | XY | d_i = 1.75 mm; d_o = 0.4 mm; 100% infill | Tensile—ASTM D638 | Highest UTS (57.7 MPa) for θ = 0°; Lowest UTS (30.8 MPa) for θ = 90°. |
| [113]| 45°/-45°; 0°/90° | 0.15 | 40 | 210 | 50 | - | d_i = 1.75 mm; d_o = 0.5 mm; 100% infill | Bending—ASTM D790; Compression—ASTM S695; Impact test—ASTM D256 | Higher UFS (+14.31%) and impact strength (+41.20%) for θ = 45°/-45°. Low influence of raster angle on the compressive strength. |
| [114]| 45°/-45°; 0°/90° | 0.25 | 50 | 210 | 60 | XY | d_i = 1.75 mm; d_o = 0.4 mm; 100% infill | Tensile—ASTM D638; Bending—ASTM D790; Impact—ASTM D256 | Higher UTS and Izod impact strength for θ = 45°/-45°; Higher UFS for θ = 0°/90°. |

The failure of tensile specimens can be influenced by raster and build orientations. Three failure modes can be defined:

- Inter-layer failure, when the failure occurs at the interface between two adjacent layers [77] (ex. the breaking of tensile specimens with ZY or ZX orientations);
- Inter-line failure (the breaking surface aligned with the raster angle—Figure 4);
- In-layer failure or in-line failure (the breaking surface is not aligned with the raster angle or the interface between two adjacent layers).

![Figure 4. Breaking surface aligned with the raster angle; (a) ISO 527-2:2012 1A specimens; (b) detail.](image-url)

Inter-line failure can be associated with reduced diffusion between the raster lines.

The occurrence of inter-line failure at the XY specimens with a unidirectional raster angle of θ = 90° is the cause for the lower tensile strength of these specimens relative to the tensile strength of specimens with θ = 0° or θ = 45°.

The effect of stress concentration in the radius area of the tensile specimens may be amplified by the raster layout, mainly in the case of the unidirectional raster [1].

The optimization of the fused filament fabrication technology certainly has to start with the prioritization of the process parameters according to their impact on the mechanical properties of the printed part. In [22] a hierarchy of the influence of six process parameters on several mechanical properties is presented. For specimens printed in the XZ orientation, the order of the influence of the process parameters on the ultimate tensile strength is considered to be: infill density, layer thickness, presence of a contour wall, head temperature, infill orientation and printing speed, while in case of the XY orientation the
order of the importance of these parameters is different: layer thickness, infill orientation, infill density, head temperature, printing speed and presence of a contour wall. This order changes when other mechanical parameters (Young’s modulus, yield strength, etc.) are monitored.

8. Discussions and Conclusions

Fused filament fabrication is a widespread technology, used in various applications, ranging from industrial manufacturing and research activities to home use. Polylactic acid is a biodegradable, low-carbon-footprint material that can be used for the fabrication of industrial products if predictable and repeatable mechanical properties are achieved in the production process.

The mechanical behavior of components made of PLA by FFF is influenced by several factors along the production chain: filament manufacturing, geometrical design, process parameters, 3D-printing equipment, ageing and post-process treatments and mechanical testing procedure.

From the process parameters most investigated in the literature, in this paper the following have been analyzed: layer thickness, printing speed, printing head temperature, build plate temperature, build orientation and raster angle.

The necessity for standardization and uniformity in the definition of process parameters is highlighted. Comparative analysis of previous research is hampered by ambiguous or incomplete definitions of certain process parameters. Furthermore, the simultaneous variation of several process parameters during the experimental investigations conduces to difficulties in pointing out the influence of each parameter considered individually.

Finally, the critical need to define suitable specimens for the mechanical testing of FFF products is revealed by the large number of tensile specimens with breakage occurring outside the gauge length. Without specific regulations, in order to reduce the errors caused by failure outside the calibrated area, testing of a higher number of specimens may be considered.

The results presented in the literature indicate that at lower layer thicknesses better interlayer diffusion is achieved, the air voids are smaller, the surface quality is better, and the mechanical properties are higher.

High printing speeds can lead to an inadequate surface quality because of the incomplete solidification of the underlying layers when the top layers are deposited.

Low printing head temperatures can cause incomplete melting, while high printing temperatures can cause unstable material flow from the printing head. Controlling heat flows by using enclosed workspace equipment can reduce the temperature gradients on the build plate.

Upright printed specimens (ZY and ZX build orientations) have considerably lower mechanical strength compared to horizontally printed specimens (XY, XZ, YX and YZ). The mechanical properties decrease with increases in the specimen positioning angle relative to the build plate.

The use of the alternating raster leads to superior mechanical properties compared to the unidirectional raster. The anisotropic behavior of PLA components made by fused filament fabrication is highly correlated with the raster parameters, build orientation and the type of failure: inter-layer failure, inter-line failure and in-layer/in-line failure.

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