

INFLUENCE OF BASIC 3D PRINTING PARAMETERS ON MECHANICAL PROPERTIES OF PLA BIOPOLYMER PRINTS BY FDM METHOD

Adrian Stelmachowicz^a, Jacek Mazur^{b*}, Paweł Cwalina^c, Sławomir Obidziński^d,
Lucia Boszorádová^e

^a Department of Food Engineering and Machines, Faculty of Production Engineering of the University of Life Sciences in Lublin; Lublin, Głęboka 28, 20-612, Poland, e-mail: adrian.stelmachowicz@up.edu.pl, ORCID: 0009-0000-8881-011X

^b Department of Food Engineering and Machines, Faculty of Production Engineering of the University of Life Sciences in Lublin; Lublin, Głęboka 28, 20-612, Poland. e-mail: jacek.mazur@up.edu.pl, ORCID: 0000-0001-5566-6932

^c Department of Agri-Food Engineering and Environmental Management, Białystok University of Technology, Wiejska 45E, 15-351 Białystok, Poland, e-mail: p.cwalina@pb.edu.pl, ORCID: 0000-0001-5768-9644

^d Department of Agri-Food Engineering and Environmental Management, Białystok University of Technology, Wiejska 45E, 15-351 Białystok, Poland, e-mail: s.obidzinski@pb.edu.pl, ORCID: 0000-0003-4678-996X

^e Slovak University of Agriculture in Nitra Faculty of Engineering Trieda Andreja Hlinku 2, 949 76 Nitra, Slovakia, e-mail: lucia.boszoradova@uniag.sk

Corresponding author: e-mail: jacek.mazur@up.edu.pl

ARTICLE INFO

Article history:

Received: October 2025
Received in the revised form:
March 2026
Accepted: April 2026

Keywords:

3D Print,
PLA,
biopolymer,
mechanical properties,
FDM

ABSTRACT

With the rapid advancement of 3D printing technology and increasing demands for production efficiency, it is essential to verify the impact of key process parameters on the mechanical properties of printed parts. Optimizing print speed, temperature, and path orientation is critical to ensuring the repeatability and durability of manufactured components, especially in engineering and industrial applications. Polylactide (PLA) is a plant-based polymer that is one of the most popular materials used in 3D printing with FDM/FFF technology. The article presents the results of a study on the mechanical properties, specifically tensile strength and bending strength, of specimens manufactured using a Creality K2 Plus 3D printer with PLA. The tests were conducted in accordance with ISO 527-2 for tensile testing and ISO 178 for bending testing on a Stable Micro Systems TA-XT plus Texture Analyser. The filament for printing was extruded on an Artime3D MK3S filament extruder to a diameter of 1.75 mm. The specimens were printed in combinations involving changes in the three crucial printing parameters: temperature (190°C, 200°C, 210°C), printing speed (100 mm·s⁻¹, 150 mm·s⁻¹, 200 mm·s⁻¹) and the layer angle (15°, 30°, 45°, 90°). The study showed that both tensile strength and bending strength are most affected by temperature. Moreover, the optimal printing parameters for the specimens were determined for tensile strength (T=210°C, V=150 mm·s⁻¹, R=0°) and bending strength (T=200°C, V=200 mm·s⁻¹, R=0°).

Introduction

The introduction should contain the relevant background to the research being carried out and include the purpose of the work and the hypothesis (if formulated). The current state of research should be presented and the most important and as recent publications should be cited. Finally, the main purpose of the work and the hypothesis (if formulated) should be presented. References should be cited by author/authors name and year of publication (Nikora, 2007; Nowak and Kowalski, 2022; Kowalski et al., 2023).

Three-dimensional printing is gaining popularity in numerous industries. Due to the reduction in production waste and the extensive customisation of manufactured workpieces, companies are widely implementing this technology. It is used in many fields, including electronics, automotive, military, agriculture, medicine, dentistry, architecture and astronomy (Crisostomo and Dizon, 2021; García-Domínguez et al., 2019; Hsueh et al., 2021; Iftekar et al., 2023; İncesu and Akderya, 2024; Wang et al., 2023). Serial 3D printing has been implemented by automotive companies, such as the Czech Škoda, to print necessary tools or car parts (Kmošek, 2022), while in the medical field, thanks to a 3D scanner and 3D printer, a model of the talus bone was created, the titanium implant of which was placed in the patient's foot (Team, 2023). The commonly applied 3D printing technologies include: Fused Deposition Modelling (FDM; material in a solid state), Selective Laser Sintering (SLS; material in a powder form), and stereolithography (SLA; material in a liquid form), of which FDM is the most popular option due to its low cost, high printing speeds and non-toxicity (Crisostomo and Dizon, 2021; Hsueh et al., 2021; Iftekar et al., 2023; Jaworska and Podsiadło, 2019; Tartakowski and Mydłowska, 2015).

Polyactide (PLA) is a material of biological origin that can be produced entirely from renewable raw materials, e.g. maize or sugar beet (Avinc and Khoddami, 2009; Huang et al., 2021; Jaworska and Podsiadło, 2019). It is considered a more environmentally friendly material than PET. The energy consumption in PLA production is 25-55% lower compared to the production of petroleum-based polymers (Avinc and Khoddami, 2009). It is a material with good mechanical strength, compostability and biocompatibility (Avinc and Khoddami, 2009; Lorkowski et al., 2025). At room temperature, it is a rigid polymer, but has a low glass transition temperature ranging between 55°C and 60°C (Avinc and Khoddami, 2009; Tartakowski and Mydłowska, 2015). Polyactide exhibits low shrinkage making it an ideal material for manufacturing high-precision workpieces (Tartakowski and Mydłowska, 2015).

The designs of FDM 3D printers vary. The most common printer design is a device with a bed moving along the X-axis and a print head moving along the Y-Z axis (e.g. BambuLab A1 or Prusa mini), or Core-XY-style printers, where the print head moves along the X-Y axis and the printer bed moves along the Z-axis (as in the case of Prusa Core One or BambuLab P1S) (Tartakowski and Mydłowska, 2015). The principle of operation of a printer of this type is the same: material, in the form of a thin thread called a filament, with a diameter of 1.75 or 2.85 mm, is fed to the print head. The filament can be supplied in two ways: using an extruder located outside the print head (bowden) or one located in the immediate vicinity of the head (direct). In the head, the material is heated to the required temperature (depending on the manufacturer, PLA ranges between 190°C and 220°C), and the filament is liquefied. Material is forced out of the nozzle (the popular nozzle opening diameter is 0.4 mm) of an extruder and deposited onto the surface of the printer bed layer by layer. 3D printers are

available in various versions that can feed multiple materials during a single manufacturing cycle. The BambuLab system is based on AMS (Automatic Material System), which enables the printer to automatically change filaments. A new development in printers is the use of several print heads attached to the printer carriage (e.g., Original Prusa XL), as well as printers with two print heads that are activated alternately (e.g., BambuLab H2D).

In recent years, 3D printing has become more accessible. The complexities of filament feeding systems, 3D model cutting programs, and printer operation have been simplified (Lorkowski et al., 2025). Programs for generating 3D printer programs are called “slicers” because of their ability to cut a 3D model into layers. Under systems such as BambuLab, Creality, and Prusa, printers have become almost self-operating. Currently, the user is only required to know what material will be used for the print, load the material into the printer tray, and enter the material used and print parameters into the model cutting program. Neither is basic knowledge of CNC machine code programming required, as the slicer generates all macros and head movements.

An FFF/FDM slicer is software that acts as an intermediary between the CAD model and the 3D printer, translating the design into a physical output. Its task is to convert a 3D model into layers that a printer can reproduce (Wang et al., 2023), generate control instructions (G-code) defining the head movement trajectories, material extrusion and process parameters (İncesu and Akderya, 2024), as well as enable the user to set key technological parameters, such as nozzle and bed temperatures, layer thickness, printing speed, fill pattern and density, the layer deposition angle and nozzle diameter (İncesu and Akderya, 2024). In modern high-performance systems, the slicer is also responsible for optimising printing quality and speed, enabling significant increases in throughput without compromising quality, thanks to advanced cutting algorithms (Kantaros et al., 2025). Consequently, the slicer is an essential intermediate stage between the design and manufacturing processes, and its settings have a direct impact on the mechanical properties, morphology, and accuracy of the final object.

In view of the rapid development, precision and miniaturisation of 3D printers (Lorkowski et al., 2025), it is necessary to reexamine the properties of materials printed on printers, such as PLA, in relation to the printing parameters. What deserves special attention are the print speeds. Standard speeds range from 50 to 70 mm·s⁻¹, but some printers can reach maximum speeds of 600 mm/s and average speeds of 300 mm·s⁻¹. Companies such as BambuLab, Creality and Prusa are competing to break new speed records (Kantaros et al., 2025).

It is therefore necessary to ask ourselves whether, in view of the current pace of development of 3D printers and printing techniques, we can maintain the existing mechanical strength of prints. This article discusses how a specimen behaves when stretched or bent, based on its printing speed of either 100 mm/s or 200 mm·s⁻¹. It also examines the significance of temperature and the arrangement of layers, highlighting their potential decisive impact. The discussion focuses on the interdependence of these three parameters, which are most often significant in the research conducted.

The aim of the research was to determine the impact of temperature, speed, and layer inclination angle on the tensile and flexural strength of PLA samples, as well as to identify the optimal combinations of these parameters.

Materials and Methods

Filament extrusion

The material needed to print the specimens was produced using an Artme3D MK3S extruder (“Desktop Filament Extruder MK3S und MK3S+ Archive,” n.d.). This is a filament extrusion machine that can be used in a domestic setting to process material from granules or shredded 3D prints, and it was used to extrude filament with a nominal diameter of 1.75 mm (with a tolerance of ± 0.05 mm). During filament extrusion, PLA granules made from Spectrum Natural PLA filament were used. The mechanical and physical properties of the studied PLA filament, such as density ($1.24 \text{ g}\cdot\text{cc}^{-1}$), tensile strength (16 kpsi in MD and 21 kpsi in TD), Young’s modulus (480 kpsi in MD and 560 kpsi in TD), elongation at break (160% in MD and 100% in TD), and tear resistance ($15 \text{ g}\cdot\text{mil}^{-1}$ in MD and $13 \text{ g}\cdot\text{mil}^{-1}$ in TD), exhibit anisotropy, which is why they were characterized in both the machine direction (MD) and transverse direction (TD), enabling a comprehensive assessment of its behaviour under various loading conditions. This allowed us to test the filament extruder.

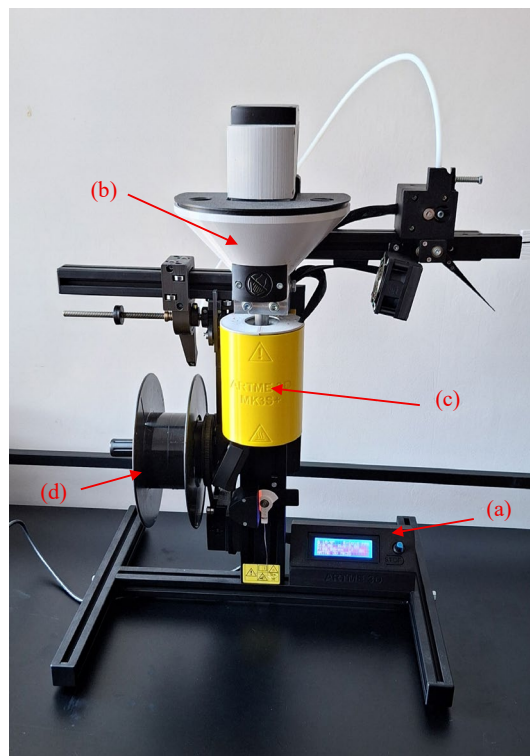


Figure 1. An Artme3D MK3S filament extruder in operation: (a) control unit, (b) granulate tray, (c) heating chamber, (d) filament winder. Image modified based on the Artme3D website (Original Desktop Filament Extruder MK3S (DIY KIT), n.d.)

The filament was extruded using the following extrusion parameters:

- extrusion temperature: 180°C;
- pressure screw rotation: 14 rpm;
- nozzle size: 1.7 mm;
- filament cooling airflow from the nozzle: 100%.

A low-compression extrusion screw (included in the extruder kit) was used. Its characteristic feature is that, compared to a high-compression screw, it has a smaller opening in the feed zone, which means that less granulate is pressed (“06-Material Voraussetzungen,” n.d.).

3D printing of specimens

The study involved preparing 36 groups of specimens with different printing parameters for measuring tensile stresses and 36 groups of specimens for measuring bending stresses. Each group contained ten specimens. During a preliminary study, the minimum number of tests was determined to be five. Considering the possibility of potential problems during printing, the number of repetitions for both tests was determined to be ten. The main objective of the study was to determine which combination of speed, temperature and layer angle had the most favourable effect on the mechanical strength of the specimens. To this end, the printing parameters crucial for the study were determined:

Later in the article, the specimen numbers will be replaced with names according to the following pattern: Tx-Vx-Rx, where T represents the printing temperature, V represents the printing speed, and R represents the layer angle.

The extruded filament was wound onto a spool and then used to print specimens on a Creality K2 Plus 3D printer (*K2 Plus Combo*, n.d.). The G-code was generated using the Creality Print software. The printer has the following parameters:

- maximum printing speed: 600 mm·s⁻¹;
- maximum acceleration: 30,000 mm·s⁻²;
- heated enclosed chamber;
- working area: 350x350x350 mm;
- maximum bed temperature: 120°C;
- maximum nozzle temperature: 350°C;
- automatic bed levelling;
- design: Core-XY.

Table 1.
Table of parameters used during specimen printing

Group number	Printing temperature (°C)	Printing speed (mm·s ⁻¹)	Layer angle (°)
1	190	100	0
2	200	100	0
3	210	100	0
4	190	100	15
5	200	100	15
6	210	100	15
7	190	100	30
8	200	100	30
9	210	100	30
10	190	100	45
11	200	100	45
12	210	100	45
13	190	150	0
14	200	150	0
15	210	150	0
16	190	150	15
17	200	150	15
18	210	150	15
19	190	150	30
20	200	150	30
21	210	150	30
22	190	150	45
23	200	150	45
24	210	150	45
25	190	200	0
26	200	200	0
27	210	200	0
28	190	200	15
29	200	200	15
30	210	200	15
31	190	200	30
32	200	200	30
33	210	200	30
34	190	200	45
35	200	200	45
36	210	200	45



Figure 2. Creality K2 Plus Combo 3D printer (Chávez Mendiola et al., 2025)

Each combination of specimens included ten pieces, totalling 360 specimens for tensile testing and 360 specimens for bending testing. The shape of the specimens for tensile testing is specified in ISO 527-2, with the specimen type being 5B. The shape of specimens for three-point bending testing was based on ISO 178, which recommends the following specimen dimensions: length $l = 80 \pm 2$ mm, width $b = 10 \pm 0.2$ mm, and thickness $h = 4 \pm 0.2$ mm.

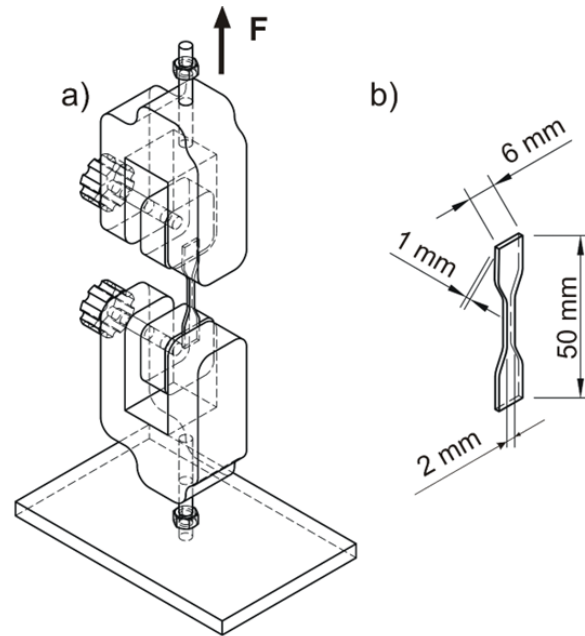


Figure 3. Specimen tensile test, with dimensions: (a) placing the specimen during testing, (b) specimen dimensions. Image modified based on an article by Mazur J. et al. (Mazur et al., 2025)

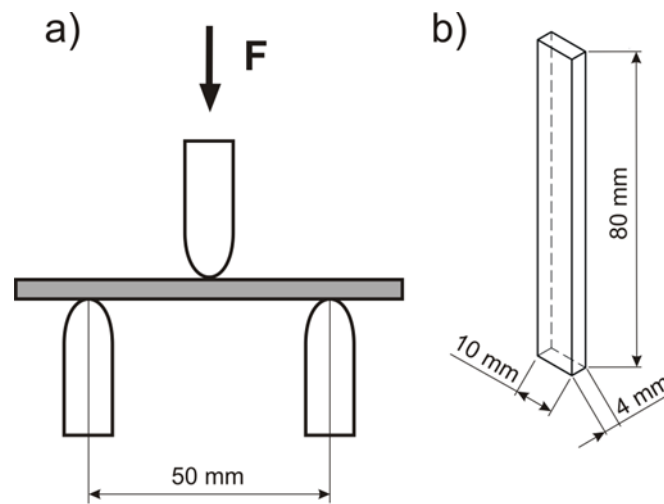


Figure 4. Test by the three-point specimen bending method, with dimensions: (a) placing the specimen on the measuring stand, (b) specimen dimensions. Image modified based on an article by Mazur J. et al. (Mazur et al., 2025)

During specimen printing, the side walls were excluded in the print parameters, so that the evenly arranged wall layers did not affect the results of tensile and bending tests.

Measurement of specimen mechanical properties

The bending strength and tensile strength were tested using a Stable Micro Systems TA-XT plus Texture Analyser (*TA.XTplus Texture Analyser* | *Stable Micro Systems Products*, n.d.). The following parameters were used for the tensile testing: a measuring head speed of 1 mm/s during the test. For the bending testing, the following parameters were used: a measuring head speed of 2 mm/s during the test, a head shift of 5 mm, and a spacing of 40 mm between the supports.

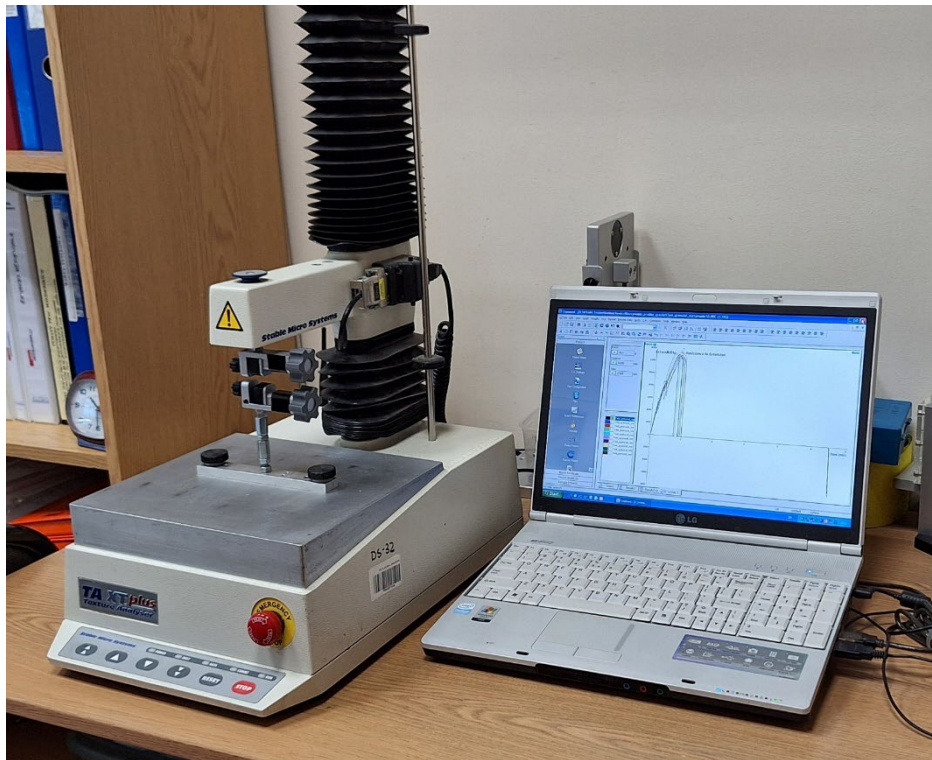


Figure 5. *Stable Micro Systems TA-XT plus Texture Analyser* (McMullen et al., 2014)

For the calculation of tensile strength, Young's modulus, bending strength and bending strain corresponding to the bending strength, the following formulas were used:

- Tensile strength (maximum tensile stress recorded during the stretching of the test specimen until it breaks) (1):

$$\sigma_m = \frac{F_m}{b \cdot h} \text{ (MPa)} \quad (1)$$

where:

- F_m – is the maximum recorded force,
- b – is the width of the measuring section,
- h – is the thickness of the measuring section.

$$\sigma_{fM} = \frac{3 \cdot F_M \cdot L}{2 \cdot b \cdot h^2} \text{ (MPa)} \quad (3)$$

Bending strength (2):

where:

- F_M – is the maximum recorded force,
- L – is the spacing between the supports,
- b – is the specimen width,
- h – is the specimen thickness.

- Bending strain corresponding to bending strength (3):

$$\varepsilon_{fM} = \frac{600 \cdot s \cdot h}{L^2} (\%) \quad (4)$$

where:

- s – is the deflection at a particular point,
- h – is the specimen thickness,
- L – is the spacing between the supports.

Statistical analysis

The results obtained were statistically analysed. Basic statistics were calculated, and an ANOVA was conducted for the factor system. The significance of the differences was determined using Tukey's test, with a significance level of $\alpha=0.05$. After completing the first three series of tests, it was demonstrated that the necessary sample size was between five and seven specimens, and the test power was above 0.94. An analysis of homogeneous groups was performed, considering the printing temperature at a significance level of $\alpha=0.05$. Outliers in each group were rejected. To examine the interactions between the factors, an ANOVA was conducted to assess the main effects (temperature, printing speed, screen ruling) on the individual parameters under analysis.

Results

Tensile stresses

Ten tests were performed for each combination of printing temperature, speed and layer angle. The data obtained was averaged. Table 2 presents the average results for the maximum tensile strength (σ_m), standard deviation, and homogeneous group for each group. Table 3

presents one-way significance tests for the tensile strength parameter; the statistically significant effects of all three factors (printing temperature, printing speed, and screen angle) are highlighted in red.

Table 2.

Table of calculation results for tensile strength (MPa) with a designation of homogeneous groups

Group	σ_m (MPa)	Standard deviations	Homogeneous group
T190-V100-R0	42.70	1.66	o, p, q
T190-V100-R15	40.15	2.09	m, n, o
T190-V100-R30	34.75	2.64	j, k
T190-V100-R45	24.39	2.07	c, d, e
T190-V150-R0	55.40	1.24	u
T190-V150-R15	46.00	2.16	q, r, s
T190-V150-R30	36.03	2.01	j, k, l
T190-V150-R45	28.58	2.38	f, g, h
T190-V200-R0	51.24	4.94	t
T190-V200-R15	46.68	1.60	r, s
T190-V200-R30	38.36	2.94	k, l, m, n
T190-V200-R45	28.78	2.31	g, h
T200-V100-R0	49.41	3.10	s, t
T200-V100-R15	27.35	3.34	e, f, g, h
T200-V100-R30	30.38	1.46	h, i
T200-V100-R45	21.78	2.05	b, c, d
T200-V150-R0	57.28	1.48	u, v
T200-V150-R15	42.87	2.13	o, p, q, r
T200-V150-R30	32.71	1.90	i, j
T200-V150-R45	25.56	1.74	d, e, f, g
T200-V200-R0	45.01	1.86	p, q, r
T200-V200-R15	39.86	2.24	l, m, n, o
T200-V200-R30	36.44	1.91	j, k, l, m
T200-V200-R45	21.54	1.03	b, c
T210-V100-R0	42.10	2.62	n, o, p
T210-V100-R15	24.97	3.28	c, d, e, f, g
T210-V100-R30	30.68	1.46	h, i
T210-V100-R45	19.36	2.27	a, b
T210-V150-R0	59.61	0.89	v
T210-V150-R15	35.69	1.83	j, k
T210-V150-R30	33.24	2.42	i, j
T210-V150-R45	24.82	2.55	c, d, e, f
T210-V200-R0	49.80	1.11	s, t
T210-V200-R15	27.28	2.68	e, f, g, h
T210-V200-R30	36.04	1.50	j, k, l
T210-V200-R45	17.56	0.97	a

*a-v - the same letters indicate that they belong to the same homogeneous group at $\alpha=0.05$

Table 3.
Results of the one-tailed significance test for the tensile strength parameter (σ_m)

	ss	Degrees of freedom	MS	Pt	p
Free expression	2256079	1	2256079	49745.40	0.0000
V (mm·s ⁻¹)	381	2	191	4.20	0.0157
T (°C)	36102	2	18051	398.02	0.0000
R (°)	302	3	101	2.22	0.0852
Error	15964	352	45		

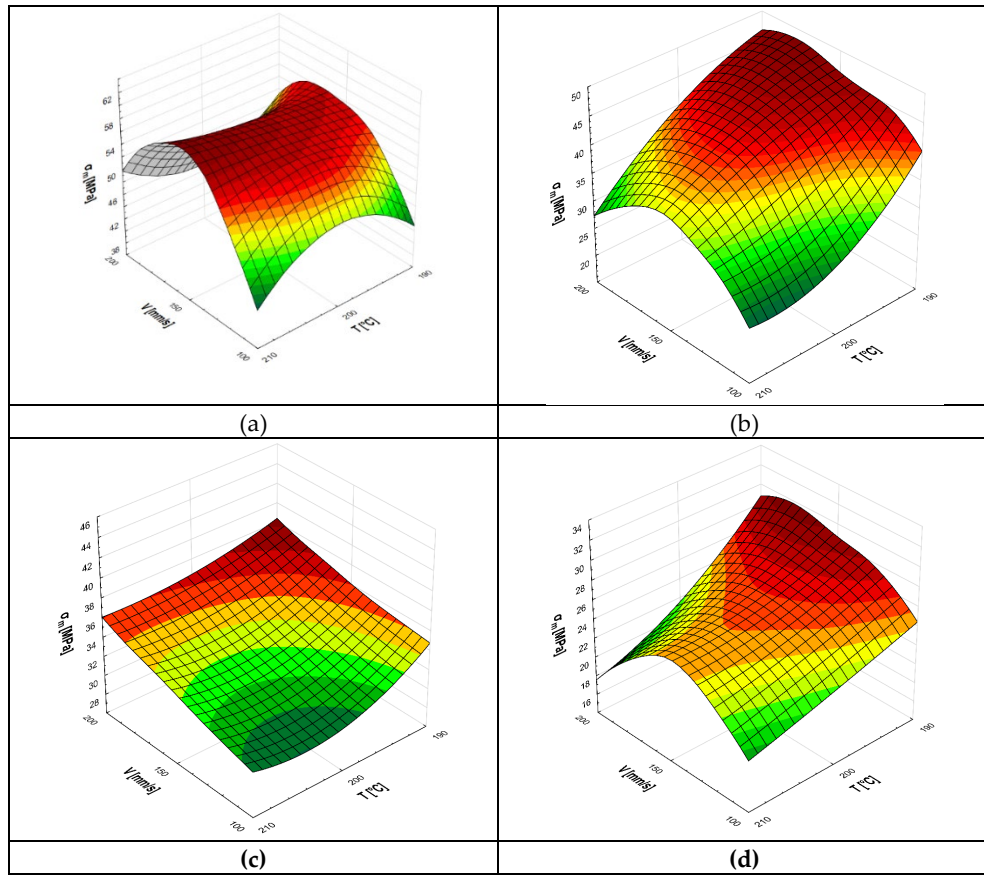


Figure 6. Tensile stress graphs: (a) for an angle $R=0^\circ$; (b) for an angle $R=15^\circ$; (c) for an angle of 30° ; (d) for an angle of 45°

It was observed that an increase in printing temperature from 190°C to 210°C resulted in an increase in tensile strength for most of the combinations tested. The highest σ_m values were obtained for specimens printed at a temperature of 210°C , a speed of $150\text{ mm}\cdot\text{s}^{-1}$, and

an angle of 0°, with an average strength of 59.61 MPa. For the same temperature, but at an angle of 45°, the strength decreased to as low as 17.56 MPa, indicating the effect of layer orientation on this parameter.

An increase in printing speed from 100 to 200 mm/s resulted in a decrease in tensile strength for most angles, except at the 30° angle, where a slight increase was observed. This may be related to a better degree of layer bonding at higher speeds and a specific angle.

The highest tensile strength values were obtained for specimens printed at an angle of 0°, regardless of the temperature and speed. As the angle increased to 45°, the strength steadily decreased, confirming the crucial role of layer orientation in the strength of 3D prints under FDM technology.

Bending stresses

Ten tests were performed for each combination of printing temperature, speed and layer angle. The data obtained was averaged. Table 4 shows the average results for the maximum bending strength, standard deviation, and the homogeneous group for each group. Table 5 presents one-way significance tests for the bending strength parameter; the statistically significant effects of printing temperature and printing speed are highlighted in red. Table 6 presents the average results for the bending strain, corresponding to the bending strength, standard deviation, and homogeneous group for each group. Table 7 presents one-way significance tests for the bending strain parameter; a statistically significant effect of print speed and screen angle is indicated in red.

Table 4.

Table of calculation results for bending strength (MPa) with a designation of homogeneous groups

Group	Bending strength (MPa)	Standard deviations	Homogeneous group*
T190-V100-R0	85.40	4.19	i, j, k, l, m
T190-V100-R15	83.48	6.29	h, i, j, k
T190-V100-R30	87.89	3.41	j, k, l, m
T190-V100-R45	92.92	2.28	m, n
T190-V150-R0	81.98	5.70	h, i, j
T190-V150-R15	85.37	2.82	i, j, k, l, m
T190-V150-R30	88.89	1.55	j, k, l, m
T190-V150-R45	90.75	3.70	k, l, m, n
T190-V200-R0	83.36	10.64	h, i, j, k
T190-V200-R15	84.52	9.75	i, j, k, l
T190-V200-R30	83.99	5.61	h, i, j, k, l
T190-V200-R45	87.65	3.13	j, k, l, m
T200-V100-R0	73.85	6.92	e, f, g

T200-V100-R15	81.56	2.93	h, i, j
T200-V100-R30	81.59	2.84	h, i, j
T200-V100-R45	84.54	4.00	i, j, k, l
T200-V150-R0	90.07	3.14	k, l, m, n
T200-V150-R15	91.18	1.86	l, m, n
T200-V150-R30	86.43	3.76	i, j, k, l, m
T200-V150-R45	91.45	2.47	l, m, n
T200-V200-R0	97.52	3.39	n
T200-V200-R15	92.66	2.27	m, n
T200-V200-R30	86.45	3.82	i, j, k, l, m
T200-V200-R45	76.40	2.33	f, g, h
T210-V100-R0	64.98	6.67	b, c, d
T210-V100-R15	66.48	5.98	c, d, e
T210-V100-R30	64.39	3.36	b, c, d
T210-V100-R45	65.83	3.74	b, c, d
T210-V150-R0	64.52	2.99	b, c, d
T210-V150-R15	70.16	1.68	d, e, f
T210-V150-R30	58.80	2.69	a, b
T210-V150-R45	55.72	2.87	a
T210-V200-R0	79.19	4.80	g, h, i
T210-V200-R15	63.42	3.75	b, c, d
T210-V200-R30	61.54	2.77	a, b, c
T210-V200-R45	65.02	2.51	b, c, d

*a–n - the same letters indicate that they belong to the same homogeneous group at $\alpha=0.05$

Table 5.

Values of the one-tailed significance test for the bending strength parameter

	ss	Degrees of freedom	MS	Pt	p
Free expression	2256079	1	2256079	49745.40	0.0000
V (mm·s ⁻¹)	381.24	2	190.62	4.20	0.0157
T (°C)	36102.1	2	18051.05	398.023	0.0000
R (°)	302.47	3	100.82	2.223	0.0852
Error	15964.09	352	45.35		

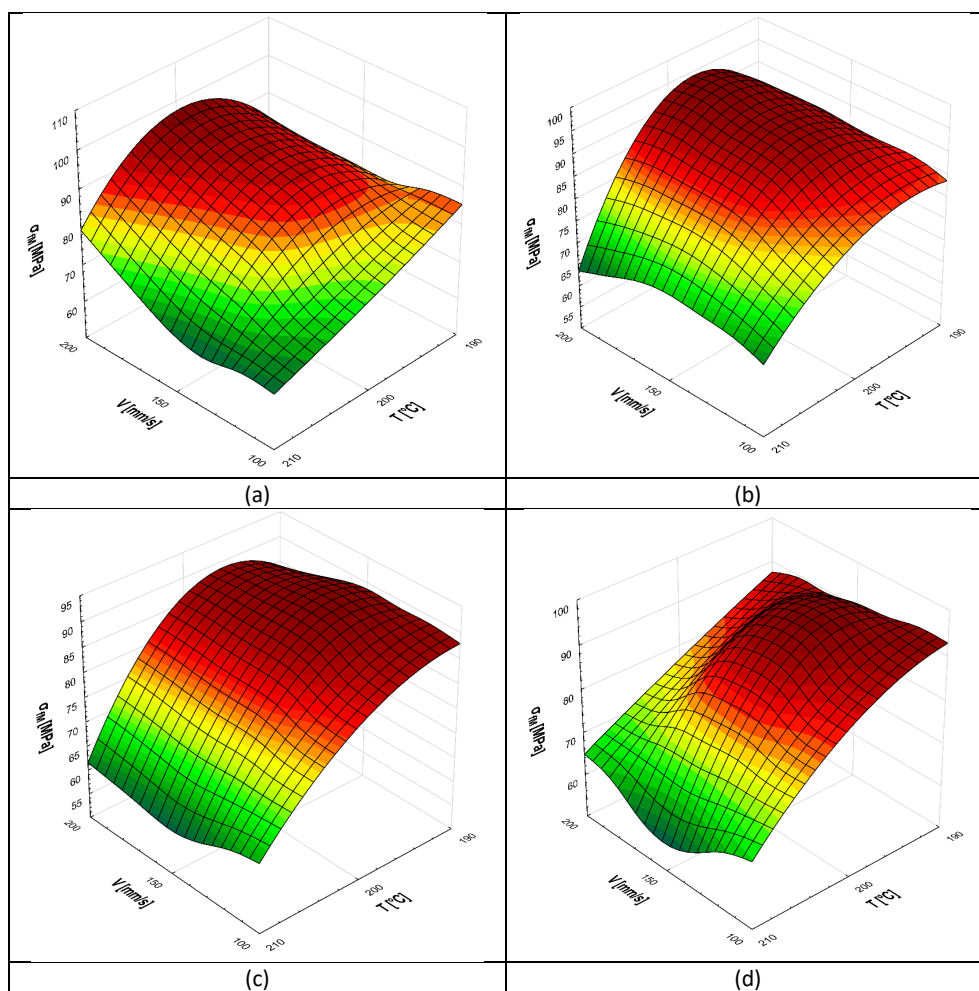


Figure 7. Bending stress graphs: (a) for an angle $R=0^\circ$; (b) for an angle $R=15^\circ$; (c) for an angle of 30° ; (d) for an angle of 45°

Table 6.
Table of calculation results for bending strains (%) with a designation of homogeneous groups

Group	Bending strain corresponding to bending strength (%)	Standard deviations	Homogeneous group*
T190-V100-R0	22.42	0.39	e, f, g
T190-V100-R15	22.12	0.46	e, f
T190-V100-R30	21.33	0.36	b, c, d
T190-V100-R45	20.68	0.33	a, b
T190-V150-R0	22.49	0.51	f, g
T190-V150-R15	22.32	0.22	e, f, g
T190-V150-R30	21.14	0.08	b, c
T190-V150-R45	21.18	0.46	b, c
T190-V200-R0	22.12	0.66	e, f
T190-V200-R15	21.67	0.72	c, d, e
T190-V200-R30	21.65	0.47	c, d, e
T190-V200-R45	21.30	0.45	b, c, d
T200-V100-R0	23.79	0.17	j, k, l, m, n
T200-V100-R15	24.32	0.21	m, n, o
T200-V100-R30	23.29	0.27	h, i, j
T200-V100-R45	22.78	0.37	f, g, h, i
T200-V150-R0	24.09	0.19	k, l, m, n, o
T200-V150-R15	23.52	0.22	i, j, k, l
T200-V150-R30	23.47	0.26	i, j, k
T200-V150-R45	22.66	0.43	f, g, h
T200-V200-R0	23.01	0.34	g, h, i, j
T200-V200-R15	23.67	0.17	j, k, l, m
T200-V200-R30	23.25	0.47	h, i, j
T200-V200-R45	22.62	0.48	f, g, h
T210-V100-R0	24.79	0.59	o
T210-V100-R15	24.55	0.46	n, o
T210-V100-R30	23.36	0.17	h, i, j, k
T210-V100-R45	20.15	0.99	a
T210-V150-R0	24.27	0.09	l, m, n, o
T210-V150-R15	24.13	0.14	k, l, m, n, o
T210-V150-R30	23.04	0.52	g, h, i, j
T210-V150-R45	22.34	0.78	e, f, g
T210-V200-R0	24.10	0.39	k, l, m, n, o
T210-V200-R15	24.42	0.26	m, n, o
T210-V200-R30	23.46	0.39	i, j, k
T210-V200-R45	22.03	0.86	d, e, f

*a–o - the same letters indicate that they belong to the same homogeneous group at $\alpha=0.05$

Table 7.

Results of the one-tailed significance test for the bending strain parameter

	ss	Degrees of freedom	MS	Pt	p
Free expression	187756.22	1	187756.22	386818.495	0.0000
V (mm·s ⁻¹)	0.704	2	0.3518	0.7247	0.4852
T (°C)	213.282	2	106.6408	219.7032	0.0000
R (°)	187.477	3	62.4924	128.7479	0.0000
Error	170.856	352	0.4854		

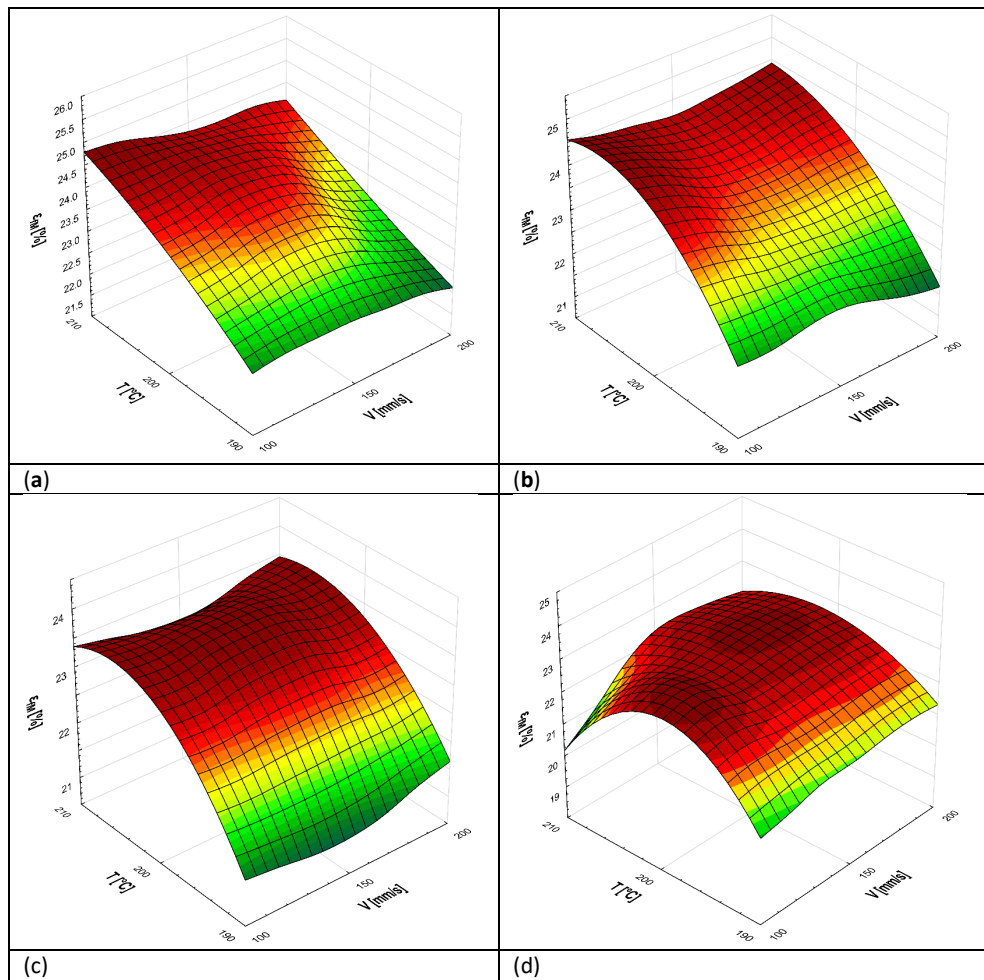


Figure 8. Bending strain graphs: (a) for an angle $R=0^\circ$; (b) for an angle $R=15^\circ$; (c) for an angle of 30° ; (d) for an angle of 45°

The bending strength was the highest for specimens printed at 200°C, a speed of 200 mm·s⁻¹, and an angle of 0° (97.52 MPa). A temperature increase above 200°C resulted in a decrease in bending strength, which may be related to excessive plasticisation of the material and deterioration of the interlayer adhesion.

An increase in the printing speed to 200 mm·s⁻¹ had a favourable effect on bending strength for an angle of 0°, while for greater angles, the effect was less pronounced.

Similar to tensile testing, specimens printed at an angle of 0° showed the highest bending strength. For an angle of 45°, these values were significantly lower.

The bending strain corresponding to the bending strength showed no significant differences between groups, suggesting that the printing parameters under analysis do not strongly influence the elasticity of the specimens.

Discussion

The tests were designed to evaluate the mechanical tensile strength and bending strength of specimens manufactured using a 3D printer with PLA.

A study (İncesu and Akderya, 2024) demonstrated that the tensile strength of specimens increases with an increase in temperature. Increasing the printing speed increases the Young's modulus for specimens printed at a temperature of 220 and 230 degrees, while increasing the printing temperature decreases the Young's modulus. However, a study (Katunin et al., 2016) suggests that printing speed has no direct effect on the mechanical strength of printed specimens.

The results obtained are consistent with observations made by İncesu and Akderya (İncesu and Akderya, 2024), who also demonstrated that an increase in the printing temperature improved the tensile strength of PLA specimens. However, with an increase in printing speed (from 25 mm/s to 50 mm/s), the strength decreases. Moreover, contrary to their study, the present study found that the layer angle has a strong influence on the effect of printing speed. A literature item (Katunin et al., 2016) suggests that the printing speed has no significant effect on the mechanical strength, which contradicts other studies. The results of the present study show that for an angle of 30°, the tensile strength increases with an increase in speed. The observed differences may be attributed to the mechanism of layer bonding during FDM printing. A higher temperature promotes better bonding of the layers. However, if the temperature is too high, it can lead to material degradation. The printing speed affects the contact time between the layers and the degree of layer bonding, which explains the varying results depending on the orientation angle. A study (Tartakowski and Mydlowska, 2015) demonstrated that the printing temperature, followed by the printing speed, are the crucial parameters affecting the strength. The same study also suggests that the strength of specimens printed using a 3D printer is slightly lower than that of specimens made using pressure injection moulding.

The layer angle proved to be a crucial parameter, as specimens printed at an angle of 0° show noticeably higher strength, confirming that the direction of force relative to the layer orientation is critical for mechanical properties.

Conclusions

Based on the present study, the following conclusions can be formulated:

1. The printing temperature has the greatest effect on both the mechanical tensile strength and bending strength of PLA specimens.
2. The printing speed has an effect on the strength depending on the layer angle: for an angle of 30° , tensile strength increases with an increase in the speed, while decreasing for other angles.
3. The layer angle has a significant effect on the strength, as specimens printed at an angle of 0° show the greatest strength, while those printed at 45° show the lowest strength.
4. Bending strain shows no significant differences depending on the printing speed, suggesting that this parameter does not significantly affect the elasticity of the specimens.
5. The optimum printing parameters for tensile strength include: $T=210^\circ\text{C}$, $V=150\text{ mm}\cdot\text{s}^{-1}$, $R=0^\circ$.
6. The optimum printing parameters for bending strength include: $T=200^\circ\text{C}$, $V=200\text{ mm}\cdot\text{s}^{-1}$, $R=0^\circ$.
7. Variations in printing temperature affect the diffusion of polymer chains across layer boundaries, enhancing interlayer adhesion and altering the material's degree of crystallinity. Higher temperatures may also reduce residual stresses, thereby influencing the overall mechanical strength of the printed parts.
8. Print speed governs the contact time between the extruded path and the previously deposited layer, directly impacting the shape and uniformity of the path cross-section. Excessive speed can result in under-extrusion, compromising interlayer bonding and introducing structural defects.
9. The angle of path deposition influences stress distribution within the print. At 0° , loads are transferred along continuous polymer fibers, whereas at 45° , stresses concentrate at path junctions, potentially creating localized weaknesses due to material discontinuity.

In the future, it would be beneficial to expand the research to explore other materials and analyse the microstructure of interlayer bonds.

Author Contributions: AS and JM conceived and designed the paper, analysed the literature and wrote the paper; JM, PS, PC, SO participated in idea conceptualization; JM collaborated during the literature analysis; PS funded the project. JM and PS supervised the project. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Funding: This research was supported by project no. SD.WTI.26.106 IM provided by University of Life Sciences in Lublin, Poland.

References

- 06-Material Voraussetzungen. (n.d.). *ARTME 3D*. Retrieved July 30, 2025, from <https://www.artme-3d.de/produkte/desktop-filament-extruder-mk3s/06-material-requirements/>
- Avinc, O., & Khoddami, A. (2009). Overview of Poly(lactic acid) (PLA) Fibre. *Fibre Chemistry*, 41(6), 391–401. <https://doi.org/10.1007/s10692-010-9213-z>
- Chávez Mendiola, E., Rivera Nieblas, J., Grijalva Acuña, J. C., Acedo-Ruiz, R., Jimenez Lopez, E., & Peinado-Gonzalez, J. (2025). *Análisis de elemento finito a eslabones de robot didáctico impreso en 3D*. 3, 35–43.
- Crisostomo, J. L. B., & Dizon, J. R. C. (2021). 3D Printing Applications in Agriculture, Food Processing, and Environmental Protection and Monitoring. *Advance Sustainable Science, Engineering and Technology*, 3(2), 0210201. <https://doi.org/10.26877/asset.v3i2.9627>
- Desktop Filament Extruder MK3S und MK3S+ Archive. (n.d.). *ARTME 3D*. Retrieved August 18, 2025, from <https://www.artme-3d.de/produkte/desktop-filament-extruder-mk3s/>
- García-Domínguez, A., Claver, J., & Sebastián, M. A. (2019). Infill optimization for pieces obtained by 3D printing. *Procedia Manufacturing*, 41, 193–199.
- Hsueh, M.-H., Lai, C.-J., Wang, S.-H., Zeng, Y.-S., Hsieh, C.-H., Pan, C.-Y., & Huang, W.-C. (2021). Effect of Printing Parameters on the Thermal and Mechanical Properties of 3D-Printed PLA and PETG, Using Fused Deposition Modeling. *Polymers*, 13(11), Article 11. <https://doi.org/10.3390/polym13111758>
- Huang, Y., Müller, M. T., Boldt, R., Zschech, C., Gohs, U., & Wießner, S. (2021). A new strategy to improve viscoelasticity, crystallization and mechanical properties of polylactide. *Polymer Testing*, 97, 107160. <https://doi.org/10.1016/j.polymertesting.2021.107160>
- Iftekar, S. F., Aabid, A., Amir, A., & Baig, M. (2023). Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review. *Polymers*, 15(11), Article 11. <https://doi.org/10.3390/polym15112519>
- Încesu, R., & Akderya, T. (2024). The Influence of Printing Speed and Temperature on the Mechanical, Absorptive, and Morphological Properties of PLA-Based Hybrid Materials Produced with an FDM-Type 3D Printer. *Polymers*, 16(19), Article 19. <https://doi.org/10.3390/polym16192771>
- Jaworska, N., & Podsiadło, H. (2019). Technologia druku 3D jako szansa dla środowiska naturalnego. *Acta Poligraphica*, 14. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-c9f05946-4dda-4200-a669-a3d3a4530987/c/AP2019_14_Jaworska_Podsiadlo.pdf
- K2 Plus Combo. (n.d.). Creality. Retrieved July 30, 2025, from <https://www.creality.com/products/creality-k2-plus-cfs-combo>
- Kantaros, A., Katsantoni, M., Ganetsos, T., & Petrescu, N. (2025). The Evolution of Thermoplastic Raw Materials in High-Speed FFF/FDM 3D Printing Era: Challenges and Opportunities. *Materials*, 18(6), Article 6. <https://doi.org/10.3390/ma18061220>
- Katunin, A., Waclawik, E., & Bilewicz, M. (2016). Wpływ parametrów technologicznych na właściwości eksploatacyjne elementów wytwarzanych techniką przyrostową FDM. *Przetwórstwo Tworzyw*, 22. <https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-366b0244-d060-4905-a20b-ac5b3cdfe22f>
- Kmošek, J. (2022, December 9). Druk 3D w motoryzacji: Jak to zrobiła Škoda Auto. *Original Prusa 3D Printers*. https://blog.prusa3d.com/pl/druk-3d-w-motoryzacji-jak-to-zrobila-skoda-auto_73147/
- Lorkowski, L., Wybrzak, K., Brancewicz-Steinmetz, E., Świniarski, J., & Sawicki, J. (2025). Influence of Print Speed on the Mechanical Performance of 3D-Printed Bio-Polymer Polylactic Acid. *Materials*, 18(8), Article 8. <https://doi.org/10.3390/ma18081765>

- Mazur, J., Sobczak, P., Panasiewicz, M., Łusiak, P., Krajewska, M., Findura, P., Obidziński, S., & Żukiewicz-Sobczak, W. (2025). Mechanical properties and biodegradability of samples obtained by 3D printing using FDM technology from PLA filament with by-products. *Scientific Reports*, 15(1), 5847. <https://doi.org/10.1038/s41598-025-89984-0>
- McMullen, R., Gorcea, M., & Chen, S. (2014). *Emulsions and their characterization by texture profile analysis* (pp. 131–154). *Original Desktop Filament Extruder MK3S (DIY KIT)*. (n.d.). ARTME 3D. Retrieved September 6, 2025, from <https://artme-3d.shop/products/original-desktop-filament-extruder-mk3s-full-diy-kit>
- Tartakowski, Z., & Mydlowska, K. (2015). Właściwości mechaniczne wyrobów wytworzonych technologią FDM. *Przetwórstwo Tworzyw*, 21(2 (164)), 171–175.
- TA.XTplus Texture Analyser | Stable Micro Systems Products. (n.d.). Retrieved August 18, 2025, from <https://www.stablemicrosystems.com/TAXTplus.html>
- Team, P. R. C. (2023, May 12). Dzięki drukowi 3D znów może chodzić: Wyjątkowa operacja w Szpitalu Uniwersyteckim w Brnie. *Original Prusa 3D Printers*. https://blog.prusa3d.com/pl/dzieki-drukowi-3d-znow-moze-chodzic-wyjatkowa-operacja-w-szpitalu-uniwersyteckim-w-brnie_77316/
- Wang, S., Chen, X., Han, X., Hong, X., Li, X., Zhang, H., Li, M., Wang, Z., & Zheng, A. (2023). A Review of 3D Printing Technology in Pharmaceuticals: Technology and Applications, Now and Future. *Pharmaceutics*, 15(2), Article 2. <https://doi.org/10.3390/pharmaceutics15020416>

WPLYW PODSTAWOWYCH PARAMETRÓW DRUKU 3D METODĄ FDM NA WŁAŚCIWOŚCI MECHANICZNE WYDRUKÓW Z BIOPOLIMERU PLA

Streszczenie. Wraz z dynamicznym rozwojem technologii druku 3D oraz rosnącymi wymaganiami dotyczącymi efektywności produkcji konieczna jest weryfikacja wpływu kluczowych parametrów procesu na właściwości mechaniczne drukowanych elementów. Optymalizacja prędkości druku, temperatury oraz orientacji ścieżki jest niezbędna do zapewnienia powtarzalności i trwałości wytwarzanych komponentów, szczególnie w zastosowaniach inżynierskich i przemysłowych. Polilaktyd (PLA) jest polimerem pochodzenia roślinnego i jednym z najpopularniejszych materiałów stosowanych w druku 3D w technologii FDM/FFF. W artykule przedstawiono wyniki badań właściwości mechanicznych, w szczególności wytrzymałości na rozciąganie i wytrzymałości na zginanie, próbek wykonanych z PLA przy użyciu drukarki 3D Creality K2 Plus. Badania przeprowadzono zgodnie z normą ISO 527-2 dla próby rozciągania oraz normą ISO 178 dla próby zginania, z wykorzystaniem analizatora tekstury Stable Micro Systems TA-XT plus. Filament do druku wytłoczono za pomocą wytłaczarki filamentu Artme3D MK3S do średnicy 1,75 mm. Próbkę drukowano w kombinacjach obejmujących zmiany trzech kluczowych parametrów druku: temperatury (190°C, 200°C, 210°C), prędkości druku (100 mm·s⁻¹, 150 mm·s⁻¹, 200 mm·s⁻¹) oraz kąta ułożenia warstw (15°, 30°, 45°, 90°). Badania wykazały, że zarówno wytrzymałość na rozciąganie, jak i wytrzymałość na zginanie są w największym stopniu zależne od temperatury. Ponadto określono optymalne parametry druku próbek dla wytrzymałości na rozciąganie (T = 210°C, V = 150 mm·s⁻¹, R = 0°) oraz wytrzymałości na zginanie (T = 200°C, V = 200 mm·s⁻¹, R = 0°).

Słowa kluczowe: druk 3D, PLA, biopolimer, właściwości mechaniczne, FDM