Effect of shells number and machining on selected properties of 3D-printed PLA samples
(*Rapid communication*)

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Abstract: Effect of shells number (1–5) on tensile properties of PLA samples printed using the FDM/FFF technique was investigated. The crack surface was also analyzed. The best properties were obtained for 4-shell sample. However, due to the large coefficient of variation (>> 10%) in the case of elongation, 3-shell sample was selected for testing the machining impact. Such a large coefficient of variation can be explained by the presence of voids between the layers. The greater the number of layers, the greater the structure defects. Machining increases surface smoothness while reducing tensile strength and practically unchanged elongation at break.

Keywords: FDM, FFF, PLA, tensile properties, machining.

Wpływ liczby warstw i obróbki skrawaniem na wybrane właściwości kształtek z PLA otrzymanych metodą druku 3D
(*Komunikat szybkiego druku*)

Streszczenie: Zbadano wpływ liczby warstw (1–5) na właściwości mechaniczne przy rozciąganiu próbek PLA otrzymanych techniką FDM/FFF. Analizie poddano także powierzchnie pęknięć. Najlepsze właściwości uzyskano dla próbki 4-warstwowej. Jednak, ze względu na duży współczynnik zmienności (>> 10%) w przypadku wydłużenia, do badań wpływu obróbki skrawaniem wytypowano próbkę 3-warstwową. Tak duży współczynnik zmienności można wyjaśnić obecnością pustych przestrzeni pomiędzy warstwami. Im większa liczba warstw, tym większe defekty struktury. Obróbka skrawaniem zwiększa gładkość powierzchni przy jednoczesnym zmniejszeniu wytrzymałości na rozciąganie i praktycznie niezmienionym wydłużeniu przy zerwaniu.

Słowa kluczowe: FDM, FFF, PLA, wytrzymałość na rozciąganie, obróbka skrawaniem.

The term 3D printing is a general term describing additive technologies whose common feature is the production of model's layer by layer [1]. These technologies first appeared in the second half of the 20th century, and their rapid development occurred in the early 21st century. Over this time, they have been implemented in industries as diverse as medicine [2], mechanics [3], engineering, and art and architecture. The main advantage of additive technologies is the ability to use a wide range of materials, such as metals, ceramic powders, polymers, as well as resins and waxes [4]. It is possible to produce models from several varied materials in a single process. The additive manufacturing process in most cases consists of four basic steps: i) preparation of the 3D model/3D scan of the model, ii) creation of an STL file, iii) obtaining physical model, iv) post processing. All mentioned steps are important in the production of functional products or prototypes. Their impact is described in a series of articles on model optimization. Anitha *et al.* [5] uses optimization techniques such as the Taguchi method, ANOVA, and correlation analysis of selected parameters to determine the most effective layer height in relation to the obtained roughness. Meanwhile, Zarylkassyn *et al.* [6] shows that layer thickness, temperature and even model orientation influence the product properties. It is equally important to properly prepare the file in the STL format. Kumar *et al.* [7] and Kamio *et al.* [8] points out that low-quality files contribute to various printing errors. Maurya *et al.* [9] provides a general overview of the most used additive technologies, including the most important parameters that should be considered when examining mechanical properties and dimensional and shape parameters. In the case of FDM/FFF (fused deposition modeling/fusion fiber fabrication)

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technology, both tensile and flexural strength increase as the filling increases and the layer height decreases [10]. The effect of infill type was investigated, and it was observed that hexagonal infill guarantees higher flexural and tensile strengths compared to other infill patterns [11]. Rheological issues were also discussed. It has been shown that the dynamic viscosity coefficient affects the anisotropy of materials and depends on the direction of layer orientation [12, 13]. Few publications have been devoted to the analysis of the effect of finishing on mechanical properties. The literature on the subject is dominated by studies on the impact of chemical or heat treatment [14–16].

Therefore, it is important to conduct research using machining of the surfaces of 3D printed samples. The aim of this work was to examine shells number impact and machining on tensile properties of PLA samples printed using FDM/FFF technique.

EXPERIMENTAL PART

Materials

Polylactide containing 1,4-dioxane-2,5-dione, 3,6-dimethyl-, (3R-cis)-, polymer with (3S-cis)-3,6-dimethyl-1,4-dioxane -2,5-dione and trans-3,6-dimethyl-1,4-dioxane-2,5-dione (PLA) was obtained from MakerBot Industries, New York, USA.

FDM/FFF printing

The specimens were obtained by FDM/FFF technique using MakerBot Sketch 3D printer (MakerBot Industries, New York, USA) equipped with an enclosed chamber, a single print nozzle and a heated table. The process parameters were temperature 220°C, table tempetature was 50°C, nozzle diameter was 0.2 mm, linear infill pattern, the shells number 1, 2, 3, 4, and 5 with width of 0.4 mm. The machined samples had 3 shells and an allowance of 0.2 mm in width compared to the unprocessed samples.

Machining of samples

Machining was performed on Herlme B 300 machining center (HERMLE AG, Gosheim, Germany) using Atorn universal end mill (HAHN+KOLB Tools GmbH, Ludwigsburg, Germany) with ZrCN Ultra-N coating and three cutting edges. The samples were mounted using a clamping element, which ensured repeatability and accuracy of dimensions. The cutting speed was 80 m/min, feed per tooth 0.02 mm/tooth. Coolant was used during cutting.

Methods

Static tensile properties were determined according to ISO 527 (sample 1BA) using an Inspekt Mini testing machine from LabMaster (Hegewald and Peschke, Nossen, Germany) at a head speed of 2 mm/min and a preload of 20 N. According to the ISO 527 standard, the width and thickness of the sample were 5 mm and 4 mm, respectively. Measurements were performed using a Mitutoyo electronic micrometer (Sakado, Japan) with an accuracy of ±0.001 mm. A Nikon AZ100 microscope/macroscope (Nikon, Minato, Japan) was used to analyze the fracture surfaces.

RESULTS AND DISSCUSION

Tensile properties

Figure 1 shows stress-strain curves of printed PLA samples. Table 1 summarizes the effect of the number of shells on the tensile properties of samples without and with machining. An increase in tensile strength was observed with an increase in shell number up to 4 shells, followed by a slight decrease. The improvement in tensile strength was approximately 22%. The difference between 1-shell and 5-shell samples was 11%. It should be emphasized that the strength of 5-shell sample was higher compared to 1- and 2-shell samples and comparable to 3-shell sample. Although the best properties were obtained for 4-shell sample, due to the large coefficient of variation (>> 10%) in the case of elongation, 3-shell sample was selected for test-

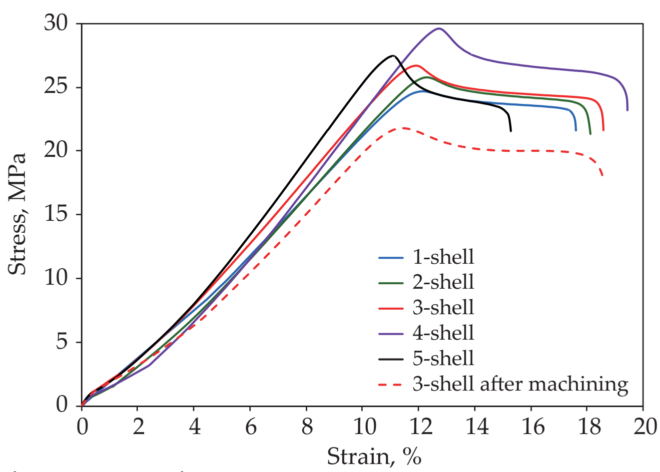

Fig. 1. Stress-strain curves

T a b l e 1. Tensile properties

Parameter	Number of shells					After machining
	1	2	3	4	5	
Tensile strength, MPa	24.1±0.4	25.6±0.8	26.3±0.5	29.3±0.5	26.7±0.5	23.9±1.0
Elongation at break, %	16.7±2.6	16.5±1.7	18.3±2.2	20.4±5.2	19.7±9.0	18.1±1.4

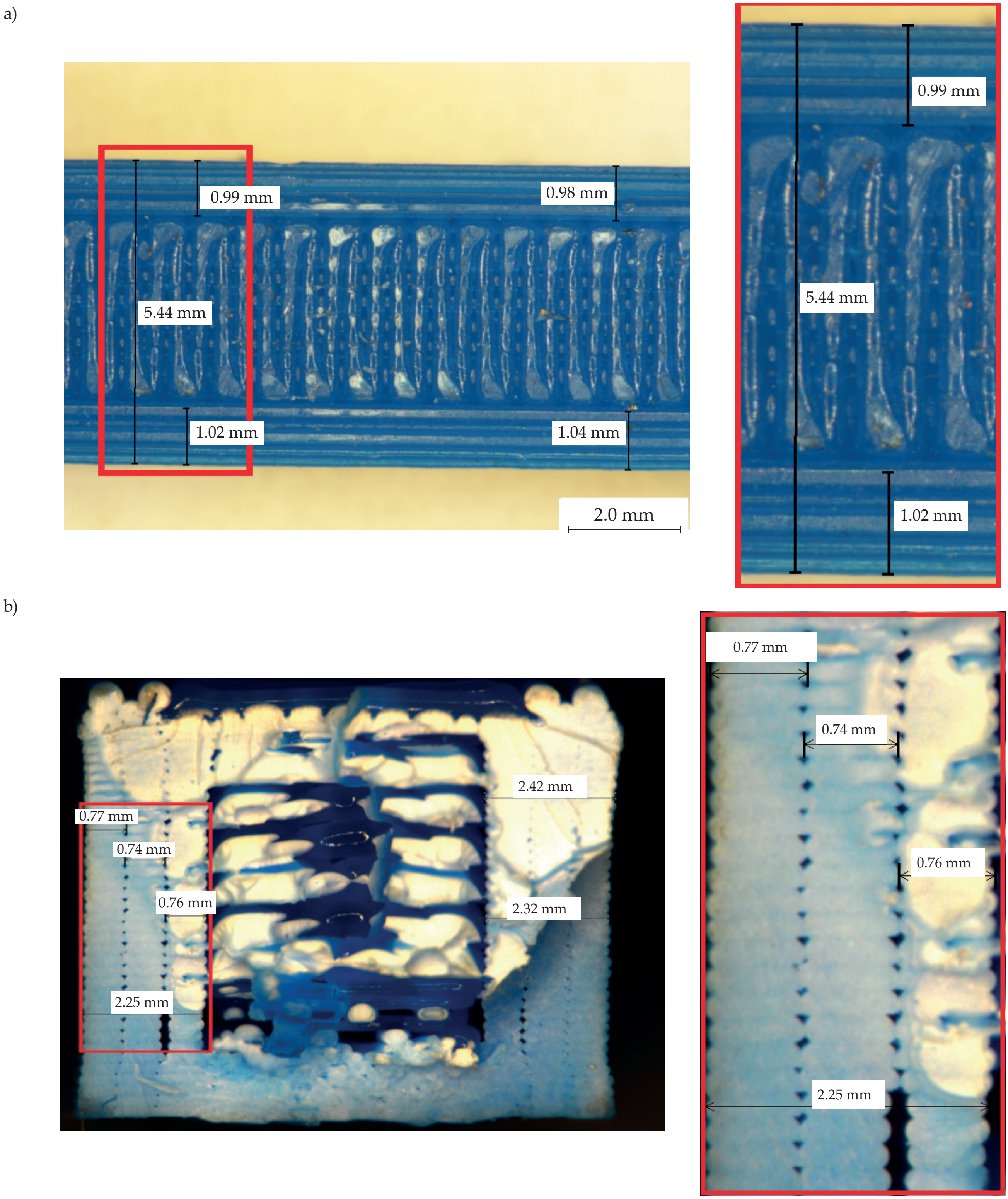

Fig. 2. Images of 3-shell sample: a) without machining, b) cross-section after the tensile test

ing the effect of machining (Fig. 2b, Fig. 3b). Such a large coefficient of variation can be explained by the presence of voids between the layers. The more layers, the more voids possible. Machining resulted in a 9% reduction in tensile strength, with unchanged elongation at break and a lower standard deviation. In the case of 3- and 5-shell samples and machined sample, a significant increase in the elongation at break compared to the other samples can also be observed.

Fracture surfaces analysis

A dimensional analysis was conducted on the contour for 3-shell sample without and with machining (Fig. 2a and

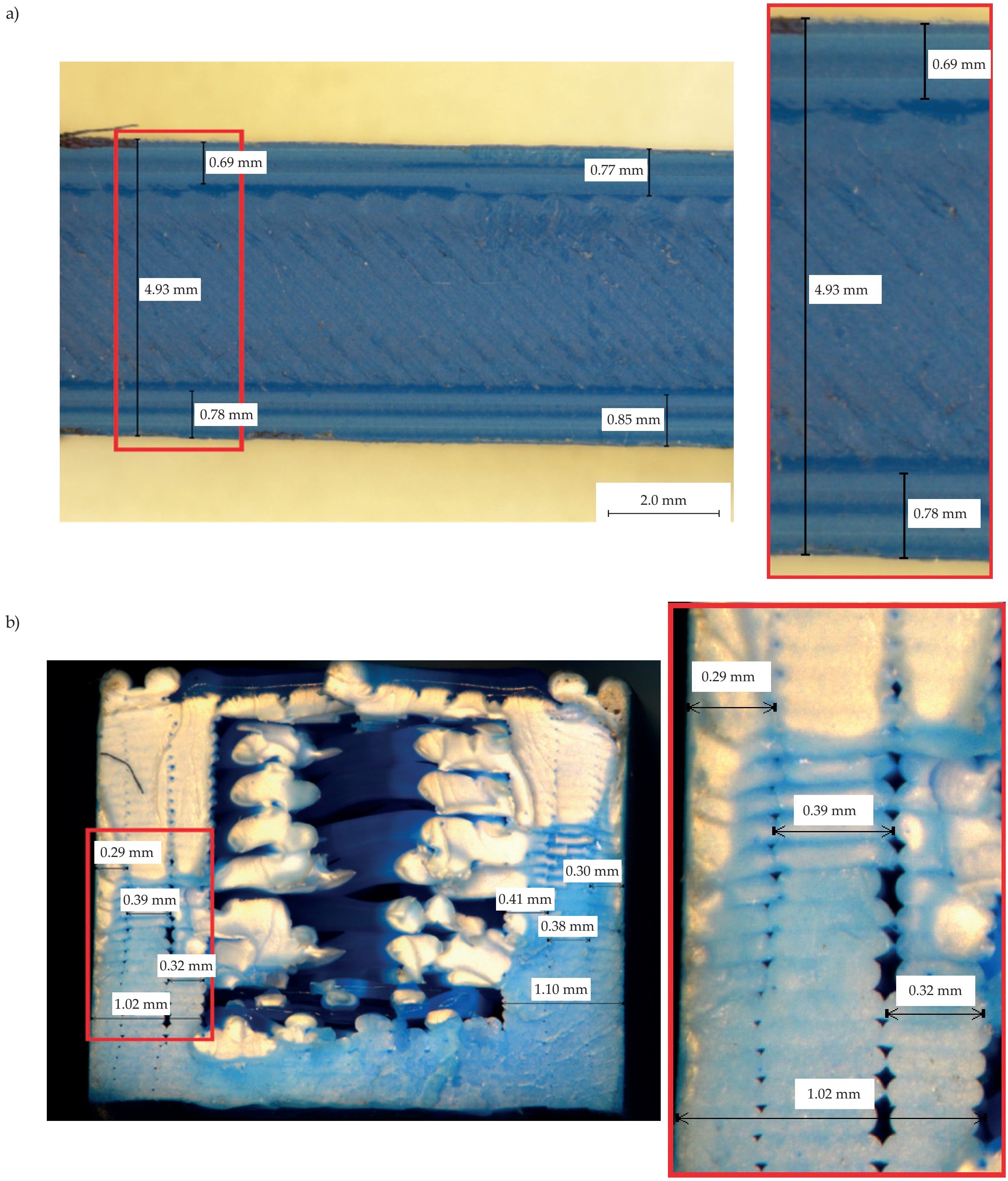

Fig. 3. Images of 3-shell sample: a) after machining, b) cross-section after the tensile test

3a). The attached images clearly show the total width of the contour and the width of the entire sample. It is worth noting that the contour width was reduced by approximately 0.4 - 0.6 mm giving a total value greater than the assumed 0.2 mm allowance. A cross-section of the broken unmachined and machined 3-shell sample is presented in Fig. 2b and Fig. 3b. Machining results in smoother edges (Fig. 3a). Edges of the sample without processing is characterized by greater waviness than after processing as an effect of 3D printing. (Fig. 2a). It can also be observed that the contour width of the machined sample after breaking is twice as small compared to the untreated sample. Importantly, the outline width changes significantly depending on the selected layer thickness during printing.

CONCLUSIONS

In this paper, a detailed analysis of shells number impact on tensile properties of PLA samples printed using FDM/FFF technique was investigated. In the case of 3-shell sample, the effect of machining was also analyzed. The tensile strength increased with the number of shells, reaching a maximum value with 4 shells. The improvement in tensile strength was approximately 22%. Machining increased surface smoothness while reducing tensile strength (9%). The elongation at break remained practically unchanged.

Author contribution

N.K. – research concept, testing, data curation, formal analysis, methodology, investigation, validation, visualization, writing; P.S. – testing, research concept, investigation, methodology, visualization, writing; M.S – testing, methodology, validation, writing; B.S – validation, writing.

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Conflict of interest

The author declare no conflict of interest.

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