Comparative analysis of selected parameters of thin-walled samples produced using FFF/FDM 3D printing technology

Analiza porównawcza wybranych parametrów próbek cienkościennych wytworzonych w technologii druku 3D FFF/FDM

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DOI: https://doi.org/10.17814/mechanik.2024.12.24

The article presents a comparative analysis of specimens produced using FFF/FDM 3D printing technology. The specimens were designed according to ISO 868. The hardness of the specimens was measured, and accuracy as well as the mass of selected colors were measured. The PLA material was chosen due to its wide application and popularity. The dimensional accuracy of the specimens was assessed. The nominal values are considered as a reference for determining the percentage accuracy for each specimens. The data obtained from this study can help to identify the optimal configurations that guide the production of components using filaments through printing.
KEYWORDS: 3D printing, PLA, thin-walled components, hardness

W artykule przedstawiono analizę porównawczą próbek wyprodukowanych w technologii druku 3D FFF/FDM. Próbki zaprojektowano zgodnie z normą ISO 868. Zmierzono twardość próbek i wykonano pomiary dokładności oraz pomiar masy wybranych kolorów. Materiał PLA został wybrany ze względu na bardzo szerokie zastosowanie i popularność. Oceniono dokładność wymiarową próbek. Wartości nominalne są uważane za odniesienie do określenia procentowej dokładności każdej próbki. Dane uzyskane z tego badania mogą pomóc zidentyfikować optymalne konfiguracje, które determinują produkcję komponentów z użyciem filamentów poprzez drukowanie.
SŁOWA KLUCZOWE: druk 3D, PLA, elementy cienkościenne, twardość

Introduction

In recent years, 3D printing technology has gained significant popularity, as evidenced by its growing use in both industry and scientific research. Optimization of components plays a key role, with thin-walled elements being used more and more often [1]. Among the various available techniques, fused deposition modeling (FDM) has emerged as the most common and widely applied method. However, achieving optimal results in the FDM process requires precise adjustment of printing parameters, which presents a considerable challenge [2]. The accuracy of 3D printing refers to the degree of dimensional conformity between the produced object and the values defined in its original design. As a result, dimensional accuracy serves as a key indicator of a device's performance, allowing an assessment of whether a 3D printer can reproduce objects in accordance with predefined parameters and design expectations. Today, filaments with additives are playing an increasingly important role [3].

Materials and the method

The most widely used 3D printing method is FDM/FFF (fused deposition modeling/fused filament fabrication) [4]. This process involves building a model layer by layer by extruding thermoplastic material through a heated nozzle. The material, softened by high temperature, is deposited in the printer's working area according to the specified geometry for each layer [5]. Once extruded, the material cools and bonds with the previous layer. Key technological parameters influencing surface quality in this method include layer thickness, filament feed rate, and path width. For the tests, specimens were manufactured using a MakerBot Sketch 3D printer. PLA (Polylactic Acid) is one of the most popular materials used in 3D printing, particularly with FDM/FFF technology. Derived from renewable resources such as corn starch or sugarcane, PLA is considered an environmentally friendly and biodegradable material. In 3D printing, [6] PLA is prized for its ability to produce detailed prints with a smooth surface finish. It has good dimensional stability, meaning it retains its shape well during and after printing. Due to its properties, PLA is commonly used for prototyping, decorative items, and educational projects where mechanical strength and high-temperature resistance are not critical. The

TABLE I. Selected mechanical properties and chemical composition of PLA [7]

Parameter	Value STD*	Value max**
Compressive strength [MPa]	17.9	93.8
Tensile strength [MPa]	46.8	65.7
Flexural strength [MPa]	61.8	94.7
Information on ingredients (>98%):	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	
Density [Mg/m^3]	1.25	

* STD or standard resolution, standard profile settings. ** Max or high resolution, 100% infill

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chemical composition of the material and selected mechanical properties are shown in table I. The data presented are for PLA material, which is produced directly by firm MakerBot

Specimens preparation

The samples were created using SOLIDWORKS (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA). Their geometric dimensions adhered to ISO 846 standards (fig. 1*b*), featuring a thin-walled design with a thickness of 2 mm (fig. 1*a*). The design was exported as an STL, then imported into MakerBot Print software (fig. 2), where the technological parameters were configured prior to starting the printing process (fig. 3).

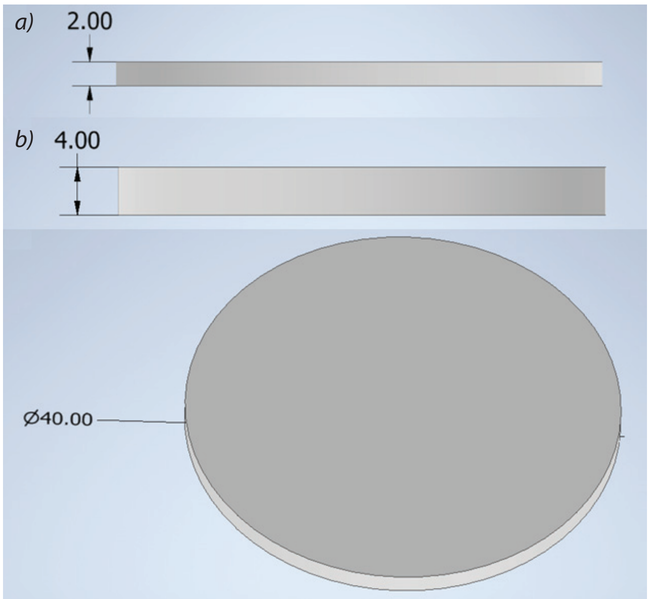

Fig. 1. Specimens: *a*) i *b*) dimensions of the specimens

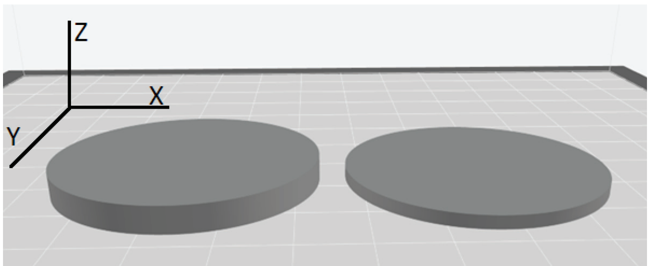

Fig. 2. Arrangement on the work platform

Fig. 3. Produced test specimens

Measurement technologies

Before conducting the primary test, a Mitutoyo digital micrometer was employed to measure the width of the measurement base as well as the actual cross-sectional dimensions of the samples. This micrometer offers a high resolution of 0.001 mm. The hardness of the samples was evaluated using a Hildebrand Shore D hardness tester. The testing procedure followed the guidelines outlined in ISO 868. The individual measurements were used to calculate the relevant values based. For weight measurements, a scale with an accuracy of 0.01 grams was used. The specimens were printed in several colors: white, red, blue, orange, green.

Results

The hardness of the specimens was evaluated using the Shore D scale method, which is commonly used for measuring the hardness of rigid plastics. The study involved testing thin-walled and standardized specimens in various colors to examine potential variations in hardness across different pigmentation and thickness. For each sample, five individual measurements were taken at different locations to ensure accuracy and minimize the effects of any surface irregularities or inconsistencies.

The average (mean) hardness value for each specimen was then calculated. This statistical analysis provides a more comprehensive understanding of the material's hardness consistency and physical properties. The results of the hardness measurements are presented in fig. 3, showcasing the average values.

The specimens were measured five times to ensure accuracy and eliminate potential measurement errors. Based on the collected data, the average value for each characteristic (thickness and diameter) was calculated, along with the standard deviation, which provides an assessment of the data's variability relative to the mean. Low standard deviation (*SD*) values indicate

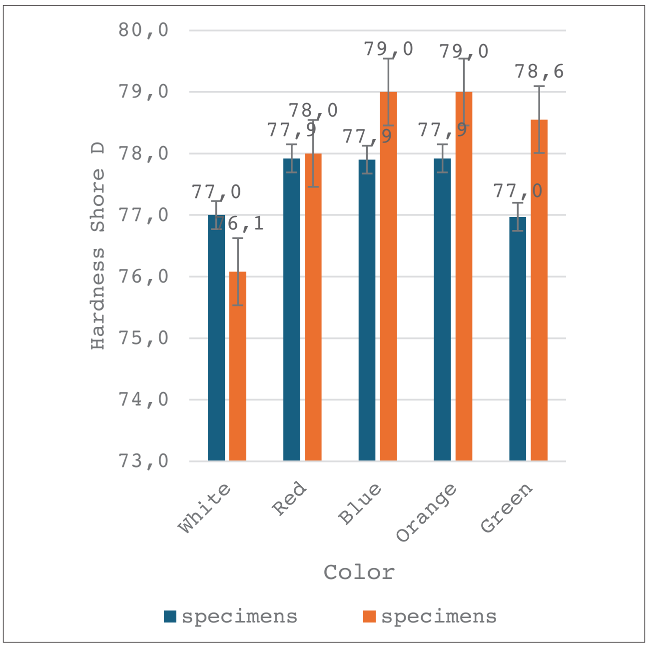

Fig. 4. Shore hardness (D scale)

TABLE. II. Specimens, measurements and standard deviation

Spacimens	4 mm				2 mm			
Color	Thickness	*SD*	Diameter	*SD*	Thickness	*SD*	Diameter	*SD*
White	5.14	0.03	40.08	0.02	2	0.02	40.08	0.03
Red	5.06	0.03	40.12	0.08	2.03	0.04	40.12	0.05
Blue	5.09	0.09	40.15	0.09	2.02	0.01	40.13	0.02
Orange	5.04	0.05	40.1	0.04	1.99	0.03	20.13	0.05
Green	5.08	0.05	40.15	0.06	2.06	0.02	40.16	0.05

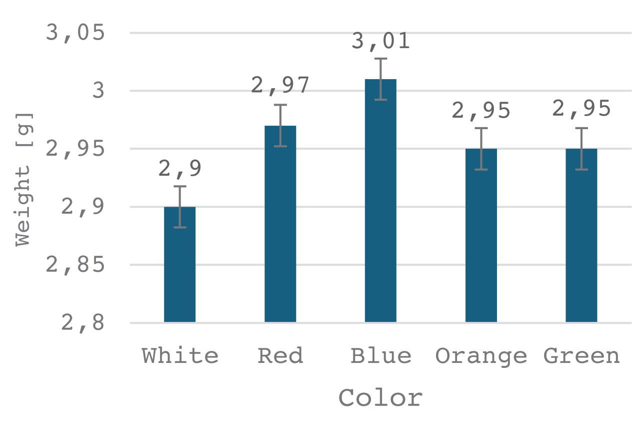

Fig. 5. Thin-walled specimens 2 mm

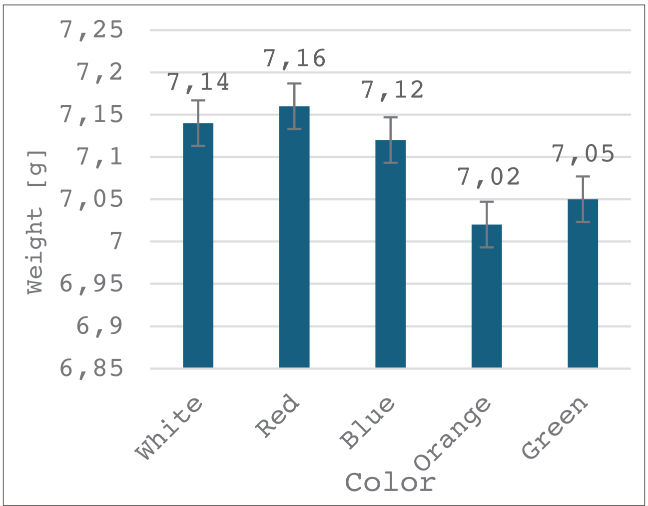

Fig. 6. Standardized specimens ISO-868

high measurement repeatability and dimensional stability of specimens, which is crucial especially for thin-walled samples, as can be seen in table II.

The graph in fig. 5 shows the weight measurements of 2 mm thin-walled specimens in different colors. The following observations can be made:

- The weight of the specimens ranges from 2.90 g (White) to 3.01 g (Blue), with a maximum difference of 0.11 g, representing a variation of approximately 3.8% across the samples.
- While the weights are consistent across colors with small variations, the Blue specimens stand out as the heaviest, whereas the White specimens are the lightest.
- The overall weight differences are minor.
- Weight differences between colors remain proportional across both specimen types, indicating that pigmentation or material properties have consistent effects on weight.

Conclusions

The most significant percentage difference is observed in Green (2.04% decrease), followed by Blue (1.39%). Red shows the smallest difference (0.13%), and Orange shows no measurable difference between thicknesses. The *SD* for thickness and diameter remains relatively low across both thicknesses, indicating consistent manufacturing and measurement precision. Notably, the *SD* for thickness is slightly higher for 2 mm specimens, likely due to the increased sensitivity of measurements for thinner samples. Standardized specimens (4 mm) are significantly heavier than thin-walled ones (2 mm), with a proportional increase in weight. The color trends remain consistent, with Blue and Red generally showing higher weights. This suggests that the difference in thickness strongly impacts weight, while the color contributes to minor variations due to material density or pigmentation additives. For most colors (Red, Blue and Green), the thinner specimens (2 mm) exhibit higher hardness values, with the largest increase observed in Green specimens (2.08% higher). Orange specimens have identical hardness values for both thicknesses, showing no change. This trend suggests that reducing thickness may enhance hardness for some colors, potentially due to differences in material cooling rates, stress distribution, or structural factors during manufacturing.

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