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Investigating the Impact of Productivity on Surface Roughness and Dimensional Accuracy in FDM 3D Printing

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Abstract

Over the past three decades, 3D printing technologies have undergone significant advancements, revolutionizing various industries, such as automotive. Additive manufacturing has played a crucial role in reducing product development time and enabling the direct printing of functional parts. One of the key advantages of additive manufacturing is its ability to provide greater design freedom compared to traditional manufacturing methods. This means that complex geometries and varying material properties can be easily printed. In this research paper, the author focused on investigating the impact of layer thickness and part orientation on the surface roughness and accuracy of printed parts. The main objective was to identify the optimal combination of layer thickness and part orientation that would yield the best results in terms of surface roughness and accuracy, considering printing time as a variable. The results from printing time, accuracy and surface roughness measurements showed that the vertical orientation is the superior for cylindrical orientation.

Keywords

FDM, PLA, surface roughness, dimensional accuracy, printing costs

1 Introduction

In various types of transport equipment, as well as in the automotive and aerospace industries, the dimensional accuracy and surface quality of components are of key importance. In addition to aesthetic issues, the accuracy, surface quality and mass of parts are also important for the operation of fittings (Takacs, 2023). Another benefit is that improved surface qualities can often reduce friction losses and increase the wear resistance (Kovács et al., 2022), leading to lower emissions (Bagdi et al., 2023; Garai et al., 2020; Vučetić et al., 2022;).

Additive manufacturing technologies have an important role to offer in the production of components, but especially in the development phase, in prototyping. However, the specific feature of these layer-by-layer build-up techniques is that the surface quality is not constant. In many cases this requires post-processing (Alzyod and Ficzere, 2023a; Ádám et al., 2020 Ádám and Weltsch, 2022;). This paper deals with the accuracy and surface quality that can be achieved by post-processing for parts produced by additive manufacturing techniques. The investigations have been carried out on parts made of PLA (Polylactic Acid), one of the most widely used materials, produced by FDM (Fused Deposition Modelling) procedure. The results are general for parts made by FDM methods.

2 Methodology

In this chapter, the author presents the principle of experiment, such as 3D printer, printing parameters and measurement of printing accuracy and surface roughness.

2.1 3D printer, material and printing method

The Prusa I3 type 3D printer was used during the experiment. PLA (Polylactic Acid) is a commonly chosen material for numerous 3D printing applications due to its excellent dimensional stability, minimal shrinkage, and ease of printing. PLA is a thermoplastic derived from renewable resources and is recognized for its ability to produce high-quality prints with a smooth surface finish (Alzyod et al., 2023; Fekete et al., 2021;). While the properties of PLA can vary depending on the specific manufacturer,

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the ranges provided in Table 1 offer a good understanding of the material's general characteristics. The printing parameters are listed in Table 2 and the input and output parameters for 3D printing are shown in Fig. 1. Printing a total of 4–4 cylindrical test pieces with 0.05, 0.1; 0.2; 0.4 mm layer thickness in case of vertical and horizontal orientation, you can acquire comprehensive understanding of how orientation affects the printing accuracy, printing time, and the surface roughness, (R_a: average surface roughness, and R_z: main roughness depth) of the printed parts. The dimensions of the workpieces were Ø20 × 50 mm. Using CAD software such as Solid Edge to model the cylinder and export an STL file is a common practice in 3D printing. The STL file format is widely utilized in 3D printing as it represents a 3D object using a series of triangles that form the object's surface. The angle formed by the planes and the specified tolerance during the export process can significantly impact the overall accuracy and quality of the printed part. In this case, the angle between the planes during exporting was set to 3°, and a tolerance of 0.05 mm was applied. Selecting the appropriate structure is crucial as it can influence not only the geometric dimensions but also the material properties (Piros and Trautmann, 2023). The printing process involved using a gyroid-type fill with a density of 30%. This particular structure is recognized for its favorable mechanical properties and is commonly employed in applications requiring high strength (Maharjan et al., 2018). When printing parts horizontally, it is often necessary to use support material to ensure the stability of the printed part throughout the printing process (Alzyod and Ficzere, 2023b). The support material serves the purpose of holding up the overhanging or cantilevered sections of the part, preventing them from collapsing or warping during printing. The design of the support material plays a critical role as it can impact the overall quality and accuracy of the printed part. Therefore, at places with inclinations up to 40° support material was utilized. This is shown with the gyroid infill in Fig. 2. Active cooling had to be used for specimens in the horizontal orientation because, as shown in Fig. 3, the support material and the specimen material were separated, causing the specimen sidewall to crack.

Table 1 Ranges of properties for PLA materials (Alzyod and Ficzere, 2022; Nugroho et al., 2018; Yao et al., 2019;)

Properties	PLA
Tensile strength (MPa)	15.5–72.2
Tensile Modulus (GPa)	2.020–3.550
Elongation at break (%)	0.5–9.2
Flexural strength (MPa)	52–115.1
Flexural modulus (GPa)	2.392–4.930
Printing temperature (°C)	190–220
Printing speed (mm/s)	40–90

Table 2 Printing parameters

Properties	PLA
Layer thickness (mm)	0.05; 0.1; 0.2; 0.4
Wall thickness (mm)	2.5
Filling density (%)	30
Printing temperature (°C)	215
Printing speed (mm/s)	40
Fill printing speed (°C)	40
Active cooling	In case of horizontal orientation

2.2 Surface roughness and accuracy measurement

Measuring the average surface roughness and main roughness depth of 3D printed parts is a crucial step in assessing

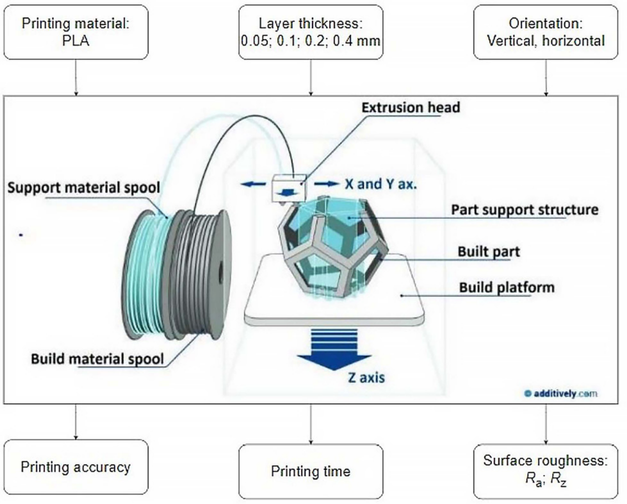

Fig. 1 The principle of printing experiment, adapted from (Kun, 2016)

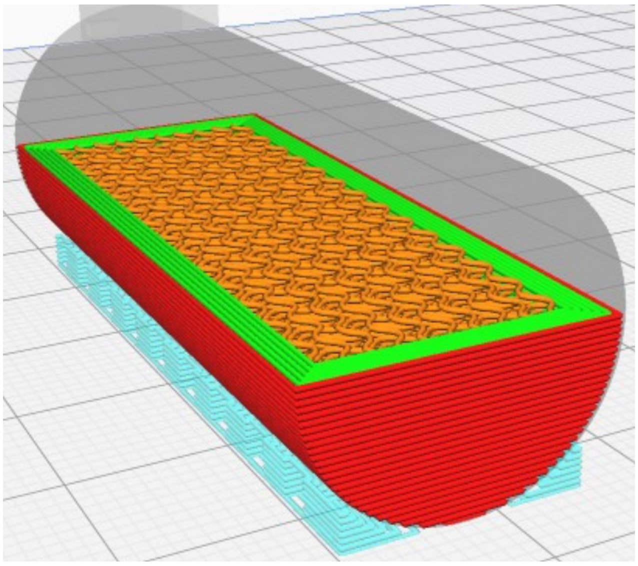

Fig. 2 Production planning for 3D printing; note: 0.4 mm layer thickness, horizontal orientation

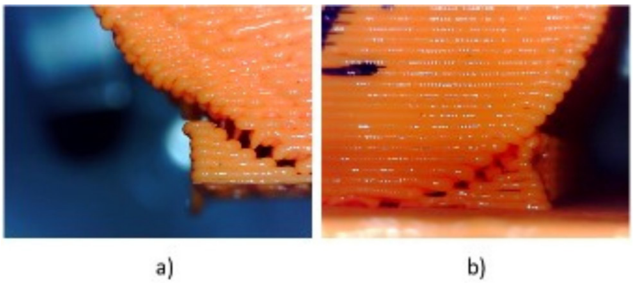

Fig. 3 Printed part (a) without active, (b) with active cooling; note: 0.4 mm layer thickness, horizontal orientation

their quality. To measure the surface roughness of the workpieces, a Mitutoyo Formtracer SV-C3100 tactile roughness tester was utilized, following the MSZ EN 4287:2022 standard (MSZT, 2002). To assess cylindricity, each point on the actual cylindrical surface must lie between two coaxial cylindrical surfaces with a radius difference within the specified tolerance (Sulinet Tudásbázis, 2023), as depicted in Fig. 4. In this study, cylindricity was measured using a Mitutoyo 543–270B dial indicator with an accuracy of 0.01 mm. The measurement aimed to evaluate the dimensional deviation from the nominal size. Unfortunately, the Roundness Measurement System could not be utilized due to the significant dimensional deviation. The measurements were taken at three planes located at distances of 5 mm, 10 mm, and 15 mm from the end of the workpiece. In each plane, four measurements were recorded at 0°, 90°, 180°, and 270°, as illustrated in Fig. 5. The obtained results were analyzed and evaluated using Microsoft Excel.

3 Results and discussion

3.1 Comparison of two orientation in terms of printing time

Printing times as a function of layer thickness in case of vertical and horizontal orientations are illustrated in Fig. 6 and Fig. 7 and the comparison of required times in case of both orientations is shown in Fig. 8. When considering the relationship between layer thickness and printing time, it can be noted that as the layer thickness increases, the printing time decreases. This trend holds true for both part orientations. However, it is worth emphasizing that regardless of the layer thickness, objects printed in the horizontal orientation generally necessitated a longer printing time compared to other orientations. The primary reason behind this disparity in printing time is the requirement to print support material. In the case of objects printed horizontally, support structures are essential to ensure the stability and integrity of the object as it is being printed. These support structures need to be carefully constructed and eventually removed, which adds an additional time overhead to the overall printing process. In contrast, when printing objects in other orientations, such as vertical or inclined, the need for extensive support structures is often reduced or eliminated altogether. This reduction in support material translates to a shorter printing time since fewer additional structures need to be printed and subsequently removed. Therefore, it can be concluded that the longer printing time associated with horizontal orientation is primarily attributed to the printing and subsequent removal of support material, whereas other orientations benefit from reduced reliance on support structures, resulting in shorter overall printing times.

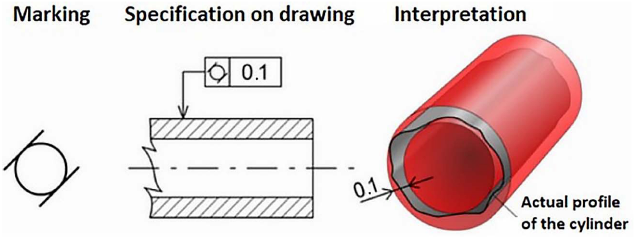

Fig. 4 The interpretation of cylindricity, adapted from (Sulinet Tudásbázis, 2023)

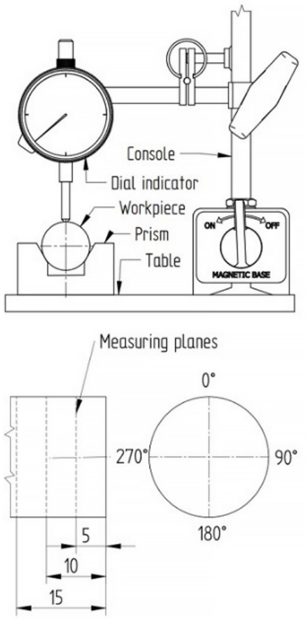

Fig. 5 Principle of accuracy measurement

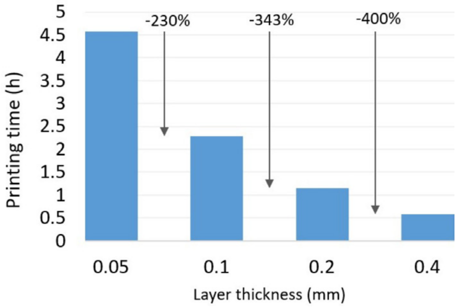

Fig. 6 Printing time evaluation as a function of layer thickness in case of vertical orientation

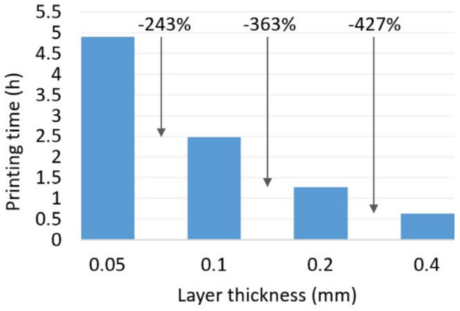

Fig. 7 Printing time evaluation as a function of layer thickness in case of horizontal orientation

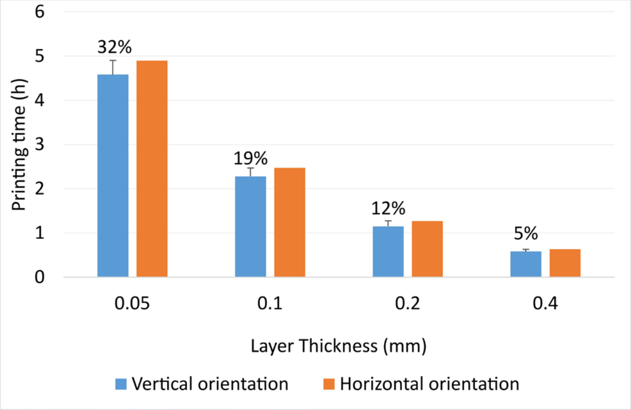

Fig. 8 Comparison of two orientations in terms of printing time

3.2 Dimensional accuracy

The dimensional accuracy of the printed workpieces as afunction of layer thickness in case of vertical and horizontal orientation are shown in Figs. 9 and Fig. 10. For objects oriented vertically, it can be generally observed from Fig. 9, that the deviation from the intended size tends to increase in the negative direction as the layer thickness increases and the printing time decreases. Another observation is that as the layer thickness increases, the allowable range of tolerances decreases. Therefore, if we can account for this dimensional variation in the design phase, we have the potential to manufacture items more efficiently and precisely, within a narrower tolerance range. By understanding these trends, we can optimize the design and production processes, ultimately enabling faster and more accurate fabrication with tighter tolerances.

When considering objects in the horizontal orientation, a closer examination of Fig. 10 reveals that the dimensional deviation from the intended size tends to increase as the layer thickness increases and printing time decreases. Simultaneously, the tolerance range decreases, reaching a minimum. Interestingly, an optimal point can be observed at a layer thickness of 0.2 mm.

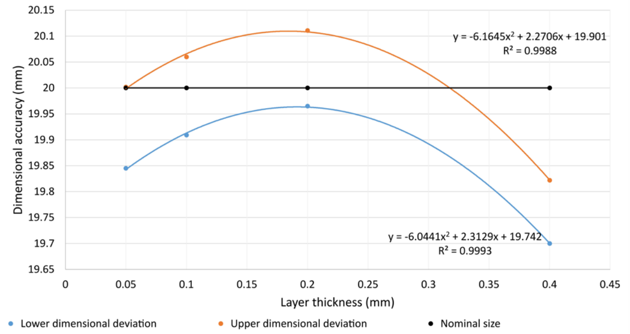

Fig. 9 Dimensional accuracy as a function of layer thickness in case of vertical orientation

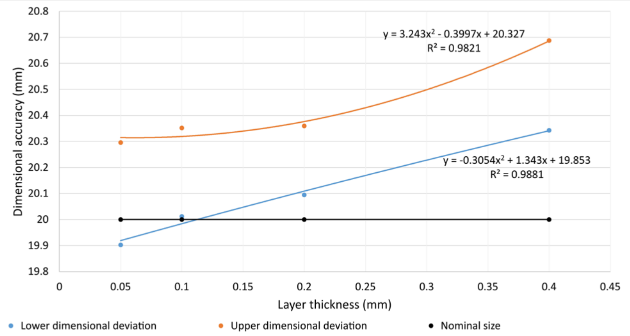

Fig. 10 Dimensional accuracy as a function of layer thickness in case of horizontal orientation

3.3 Surface roughness evaluation

The average surface roughness (R_a) and main roughness depth (R_z) as a function of layer thickness in case of vertical and horizontal orientation are illustrated in Fig. 11 and Fig. 12. Based on the analysis of Fig. 11, it is evident that the surface roughness degradation of test objects printed in the vertical orientation increases exponentially as the layer thickness increases. Considering that these parts will undergo finishing by turning, it can be inferred that printing with a layer thickness of 0.4 mm would be the most efficient approach to minimize printing time, and consequently, reduce costs, as depicted in Fig. 6. However, as illustrated in Fig. 13, using a layer thickness of 0.4 mm leads to printing errors. Alternatively, for layer thicknesses of 0.1 mm and 0.2 mm, a negligible increase in roughness is observed, but the printing time is halved compared to the 0.1 mm layer thickness. Therefore, it is advisable to opt for a 0.2 mm layer thickness for vertically oriented workpieces. By selecting a 0.2 mm layer thickness, we can strike a balance between surface roughness and printing time. This choice minimizes roughness degradation while significantly reducing the printing time, ultimately enhancing the efficiency of the additive manufacturing process. The aforementioned trend regarding surface roughness

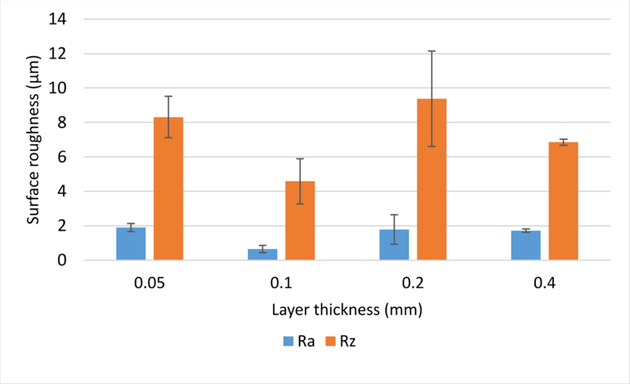

Fig. 11 R_a, R_z as a function of layer thickness in case of vertical orientation

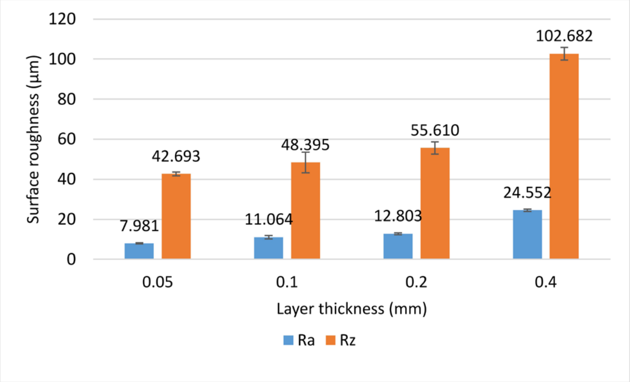

Fig. 12 R_a, R_z as a function of layer thickness in case of horizontal orientation

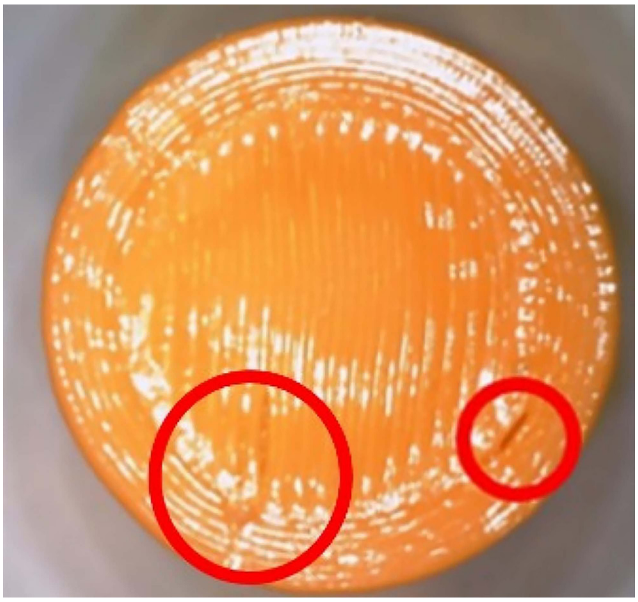

Fig. 13 Printing error; note: 0.4 mm layer thickness, vertical orientation

is not applicable to objects in the horizontal orientation. In this case, the surface roughness shows only minimal decrease with increasing layer thickness, as illustrated in Fig. 12. However, a significant reduction in roughness is observed for a layer thickness of 0.1 mm. The intersection point of the printing time and average surface roughness curve is closer to a layer thickness of 0.2 mm, indicating that this value can be considered the optimum for printing in the horizontal orientation.

It is important to note that the results of the two orientations cannot be directly compared. This is primarily because, in the vertical orientation, the measurements were taken perpendicular to the printed layers, while in the horizontal orientation, the measurements were taken parallel to the layer orientation. This difference in measurement orientation is due to the significant variation in roughness between the two orientations.

4 Conclusion

The aim of this paper was to investigate the effects of layer thickness and orientation of workpieces on the printing time, accuracy and surface roughness of the printed parts.

The author states the following conclusions:

- Printing times were shorter for all layer thickness values in the vertical orientation than in the horizontal orientation. However, this time difference decreased exponentially with increasing layer thickness.
- The dimensional accuracy is twice as bad in the horizontal orientation as in the vertical orientation. In case of vertical orientation, the deviation from the intended size tends to increase in the negative direction as the layer thickness increases and the printing time decreases, however, the tolerance field was decreased. A layer thickness of 0.4 mm would be the best if there were no printing defects, as shown in Fig. 13, so a layer thickness of 0.2 mm is the best. In case of horizontal orientation, the dimensional deviation from the intended size tends to increase as the layer thickness increases and printing time decreases.
- The surface roughness degradation of test objects printed in the vertical orientation increases exponentially as the layer thickness increases. However, in case of horizontal orientation, the surface roughness shows only minimal decrease with increasing layer thickness. It is important to note that the results of the two orientations cannot be directly compared. This is primarily because, in the vertical orientation, the measurements were taken perpendicular to the printed layers, while in the horizontal orientation, the measurements were taken parallel to the layer orientation.

- In case of horizontal orientation, the removal of support material from the specimens required more time, so overall, for cylindrical parts, the vertical orientation is preferable.

References

Alzyod, H., Ficzere, P. (2023a) "Material-Dependent Effect of Common Printing Parameters on Residual Stress and Warpage Deformation in 3D Printing: A Comprehensive Finite Element Analysis Study", Polymers, 15(13), 2893. https://doi.org/10.3390/polym15132893

Alzyod, H., Ficzere, P. (2023b) "Optimising fused filament fabrication process parameters for quality enhancement of PA12 parts using numerical modeling and Taguchi method", Heliyon, 9(3), e14445. https://doi.org/10.1016/j.heliyon.2023.e14445

Alzyod, H., Ficzere, P. (2022) "The Influence of the Layer Orientation on Ultimate Tensile Strength of 3D Printed Poly-lactic Acid", Jordan Journal of Mechanical and Industrial Engineering, 16(3), pp. 361–367.

Alzyod, H., Takacs, J., Ficzere, P. (2023) "Improving surface smoothness in FDM parts through ironing post-processing", Journal of Reinforced Plastics and Composites, 0(0), 07316844231173059. https://doi.org/10.1177/07316844231173059

Ádám, B., Weltsch, Z. (2022) "Thermal and Mechanical Assessment of PLA-SEBS and PLA-SEBS-CNT Biopolymer Blends for 3D Printing", Applied Sciences, 2021, 11(13), 6218. https://doi.org/10.3390/APP11136218

Ádám, B., Polgár, B., Nagy, D. (2020) "The effect of different printing parameters on mechanical and thermal properties of PLA specimens", Gradus, 7(3), pp. 166–173. https://doi.org/10.47833/2020.3.ENG.001

Bagdi, Zs., Csámer, L., Bakó, G. (2023) "The green light for air transport: sustainable aviation at present", Cognitive Sustainability, 2(2). https://doi.org/10.55343/cogsust.55

CAD software "Solid Edge, (2024)", [computer program] Available at: https://solidedge.siemens.com/en/solutions/products/complete-product-development-portfolio/solid-edge-2024/ [Accessed: 09 November 2023]

Fekete, I., Ronkay, F., Lendvai, L. (2021) "Highly toughened blends of poly(lactic acid) (PLA) and natural rubber (NR) for FDM-based 3D printing applications: The effect of composition and infill pattern", Polymer Testing, 99, 107205. https://doi.org/10.1016/j.polymertesting.2021.107205

Garai, F., Béres, G., Weltsch, Z. (2020) "Development of tubes filled with aluminium foams for lightweight vehicle manufacturing", Materials Science and Engineering: A, 790, 139743. https://doi.org/10.1016/j.msea.2020.139743

Kovács, Z. F., Viharos, Z. J., Kodácsy, J. (2022) "Improvements of surface tribological properties by magnetic assisted ball burnishing", Surface and Coatings Technology, 437, 128317. https://doi.org/10.1016/j.surfcoat.2022.128317

Kun, K. (2016) "Reconstruction and development of a 3D printer using FDM technology", Procedia Engineering, 149, pp. 203–211. https://doi.org/10.1016/j.proeng.2016.06.657

Maharjan, G. K., Khan, S. Z., Riza, S. H., Masood, S. H. (2018) "Compressive behaviour of 3D printed polymeric gyroid cellular lattice structure", IOP Conference Series: Materials Science and Engineering, 455, 012047. https://doi.org/10.1088/1757-899X/455/1/012047

MSZT (2002) "MSZ EN ISO 4287:2002 Geometrical product specifi-ca-tions (GPS). Surface texture: Profile method. Terms, definitions and surface texture parameters (ISO 4287:1997)", Hungarian Standards Institution, Budapest, Hungary.

Nugroho, A., Ardiansyah, R., Rusita, L., Larasati, I. L. (2018) "Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing", Journal of Physics: Conference Series, 1130, 012017. https://doi.org/10.1088/1742-6596/1130/1/012017

Piros, A., Trautmann, L. (2023) "Creating interior support structures with Lightweight Voronoi Scaffold", International Journal on Interactive Design and Manufacturing, 17, pp. 93–101. https://doi.org/10.1007/s12008-022-01182-8

Sulinet Tudásbázis "Tűrések és illesztések" (Tolerances and fits), [online] Available at: https://tudasbazis.sulinet.hu/hu/szakkepzes/mezogazdasag/muszaki-alapismeretek/alakturesek/alakturesek [Accessed: 28 June 2023] (in Hungarian)

Takacs, A. (2023) "Safe In and Out of the Car", In: Jármai, K., Cservenák, Á. (eds.) Vehicle and Automotive Engineering 4. VAE 2022. Lecture Notes in Mechanical Engineering, Springer, pp. 63–70. ISBN 978-3-031-15210-8 https://doi.org/10.1007/978-3-031-15211-5_6

Vučetić, A., Sraga, V., Bućan, B., Ormuž, K., Šagi, G., Ilinčić, P., Lulić, Z. (2022) "Real Driving Emission from Vehicle Fuelled by Petrol and Liquefied Petroleum Gas (LPG)", Cognitive Sustainability, 1(4). https://doi.org/10.55343/cogsust.38

Yao, T., Deng, Z., Zhang, K., Li, S. (2019) "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations", Composites Part B: Engineering, 163, pp. 393–402. https://doi.org/10.1016/J.COMPOSITESB.2019.01.025