A Theoretical-Experimental Study on the Influence of FDM Parameters on the Dimensions of Cylindrical Spur Gears Made of PLA

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ABSTRACT

This paper presents the results of a theoretical-experimental study on the influence of FDM parameters (height of the deposited layer at one pass H_s and percentage of filling P_u) on the dimensions of cylindrical spur gears made of PLA (shaft diameter d and bore diameter D). In this context, we designed the 3D model of a cylindrical gear with module m= 1 and z= 60 spur teeth, which we used for FDM 3D printing of 27 PLA parts with different values of coating height deposited at a pitch H_s of 0.10, 0.15, 0.20mm and different values 50, 75, and 100% of filling percentage P_u. The 324 values obtained from measuring the diameters d and D of 27 cylindrical spur gears made of PLA and the calculated values of statistical indicators (arithmetic mean, standard deviation, dispersion) were used to determine the dimensional accuracy of the analyzed parts. The study results show that the percentage of filling has a greater influence than the shaft diameter on the dimensional accuracy of cylindrical spur gears made of PLA.

Keywords-3D printing; FDM parameters; experimental test; spur gears

I. INTRODUCTION

Nowadays, production processes are undergoing transformations in terms of flexibilization according to market requirements, the main objective being to reduce costs in order to strengthen market position and maintain sustainable competitive advantage [12-17]. Additive manufacturing technologies are a viable solution for many industries such as automotive, aerospace, and defense due to advantages in comparison with formative and subtractive manufacturing technologies, e.g. the manufacturing costs are significantly reduced, complex geometries are achieved without special base and fixing elements, simplicity in use, material waste is negligible, use of bio materials, etc. [1, 6, 11].

Fused deposition modeling is one of the most popular manufacturing technologies due to its affordability, the wide range of materials used, and the possibility of customization for printed parts. However, this technology has certain limitations such as run time and surface quality. Depending on the field of use of the manufactured part, the limitations can be adjusted from the process parameters: the height of the layer deposited in one step, the filling percentage, the printing speed, etc. [9, 10]. The materials used for FDM are thermoplastics, the most popular among them being PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PET (polyethylene terephthalate), Nylon, and PC (polycarbonate) [3]. The study of the influence of 3D printing parameters has attracted the scientific interest. Authors in [1] showed a comparative study about dimensional accuracy from errors of FFF printed spur gears using PLA and Nylon and authors in [11] showed a development of a prediction system for 3D printed part deformation using SLS technology.

The novelty of this work consists in the theoretical-experimental determination of the influence of FDM parameters on the dimensions of cylindrical spur gears (shaft diameter d and bore diameter D) made of PLA. The greater influence between the two studied parameters H_s and P_u is found with statistical calculations following the measurements.

II. 3D PRINTING OF CYLINDRICAL SPUR GEARS

The quality of the parts manufactured additively by thermoplastic extrusion is influenced by the material type and the 3D printer used, [9, 10]. In this context, PLA filament with a diameter of 1.75mm (Verbatim brand) and the Creality CR-X 3D printer with a printing volume of 300×300×400mm and XY positioning accuracy of ±0.10mm were used to manufacture all cylindrical spur gears. Figure 1 shows the steps taken to perform the experimental study on the influence of FDM parameters on the dimensions of cylindrical spur gears R_d made of PLA.

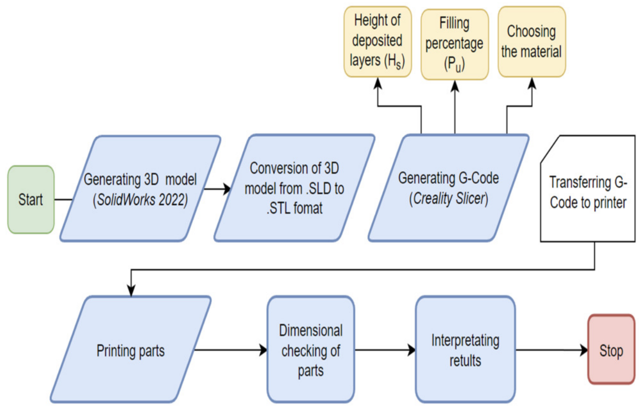

Fig. 1. Stages of the experimental study on the influence of FDM parameters on the dimensions of cylindrical spur gears fabricated from PLA.

Using the Solidworks 2022 software, the 3D model of a cylindrical spur gear with module m=1 and z=60 was designed using the ToolBox function and was converted from SLD to STL format, [6, 7, 20]. The 3D model was the basis for the 2D drawing shown in Figure 2 of [6]. Using the STL format file, corresponding to the spur gear with spur teeth shown in Figure 2, and the Creality Slicer of the Creality CR-X 3D printer, we inserted the printing parameters shown in Table I and generated the G-Code file [6, 7]. The FDM 3D printing parameters of PLA spur gears (R_d) with module m= 1 and z= 60 spur teeth, shown in Table I, fall into two categories, constant parameters and variable parameters, [5-8]. We transferred the G-Code file to the Creality CR-X printer and fabricated 27 cylindrical gears R_d from PLA with modulus m= 1 and z= 60 spur teeth. Figure 3 shows the cylindrical toothed wheel R_d made of PLA with m= 1 and z= 60 in Creality Slicer, generated by using the height of the deposited layer at one pass H_s=0.10mm, filling percentage P_u= 50%, printing speed V_p=80mm/min, and filling pattern type line oriented at 45° [8].

TABLE I. PARAMETERS OF 3D FDM PRINTING OF R_d SPUR GEARS WITH m=1 AND z=60

Constant parameters	**Variable parameters**		**Coding of the gear set**	**Material**
Part orientation X, Y	Height of the deposited layer H_s	Filling Percentage P_u	R_di	PLA
	(mm)	(%)	(i = 1… 9)	(parts)
Temperature of the extruder, T_e= 210°C	0.10	100	R_d1	3
		75	R_d2	3
		50	R_d3	3
Table temperature, T_b= 60°C	0.15	100	R_d4	3
		75	R_d5	3
		50	R_d6	3
Printing speed, V_p= 80mm/s	0.20	100	R_d7	3
		75	R_d8	3
Filling pattern - Lines 45°		50	R_d9	3

The mass of the cylindrical gear with modulus m=1 and spur teeth z=60, shown in Figure 2, is 14g (equivalent to 4.957m of PLA filament) and its running time is 2 hours and 53 minutes. The G-Code file of the cylindrical gear shown in Figure 2 contains 108500 control lines [8].

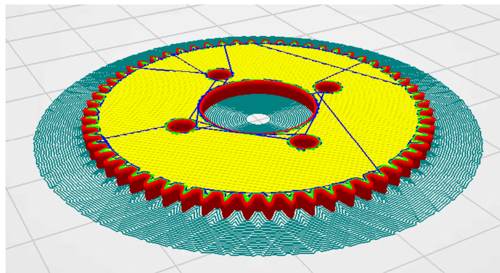

Fig. 2. R_d PLA cylindrical gear with m=1 and z=60 spur teeth (H_s=0.10 mm, P_u=50%, V_p=80mm/min, 45° oriented line fill pattern) in Creality Slicer.

III. DETERMINATION OF THE INFLUENCE OF FDM PARAMETERS ON THE DIMENSIONS OF SPUR GEARS MADE OF PLA

A. *Working Methodology*

For the experimental study we used 324 values obtained by measuring with a digital caliper the diameter of the shaft (d=62±0.1mm) and the diameter of the bore (D=20.2±0.1mm) of 27 cylindrical gears made of PLA, with m=1 and z=60, additively manufactured by thermoplastic extrusion (using the parameters in Table I). Each part was measured as shown in Figure 3. The 324 values are used to determine the arithmetic mean (1), standard deviation (2), and dispersion (3), corresponding to each set of cylindrical gears R_di in PLA with m=1 and z=60 [1, 18, 19]:

$$\bar{x} = \frac{x_1+x_2+\ldots+x_n}{n} \quad (1)$$

$$\sigma = \sqrt{\frac{\sum(x_i-\bar{x})^2}{n}} \quad (2)$$

$$\sigma^2 = \frac{1}{n}\sum(x_i-\bar{x})^2 \quad (3)$$

A set of cylindrical gears R_di made of PLA, with m=1 and z=60, contains 3 parts characterized by the same 3D printing parameters (see Table I). Two sets of measurements were performed for each part, resulting in 12 values - 6 values for shaft diameter d and 6 values for bore diameter D, as shown in Figure 3.

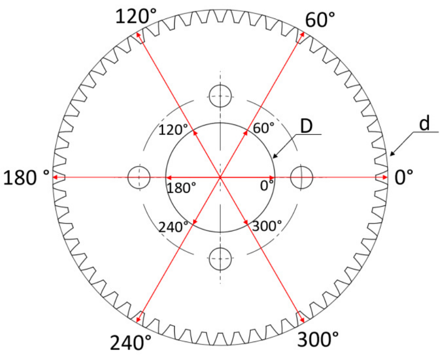

Fig. 3. Measuring points of the diameters of cylindrical gears R_d made of PLA with modulus m=1 and spur teeth z=60.

B. Results

The 324 values resulting from the measurement of the diameters of the 27 cylindrical gears R_d made of PLA, additively manufactured by thermoplastic extrusion, are graphically represented in Figures 4-21. Tables II-XIX show the results obtained from the calculation of statistical indicators arithmetic mean, standard deviation, and dispersion. The variation of the values of the arithmetic means $\bar{x}$ of the shaft diameter d for each set of R_di gears (i= 1...9) is shown in Figure 23. The variation of the values of the arithmetic means $\bar{x}$ of the bore diameter D for each set of gears R_di (i= 1...9) is shown in Figure 22.

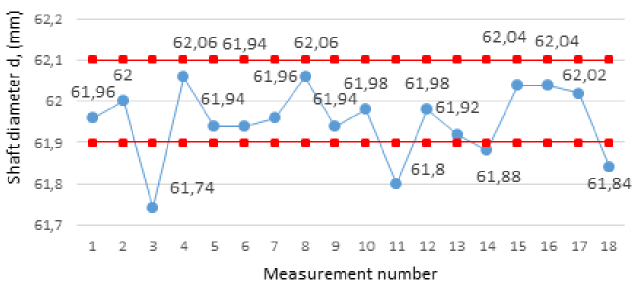

Fig. 4. Values of shaft diameter d for gear set R_d1.(H_s = 0.10mm, P_u= 100%).

TABLE II. VALUES OF THE STATISTICAL INDICATORS FOR THE SET OF SPUR WHEELS R_D1

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10mm,	**mm**	**mm**	**mm**
P_u=100%	61.95	0.086	0.007

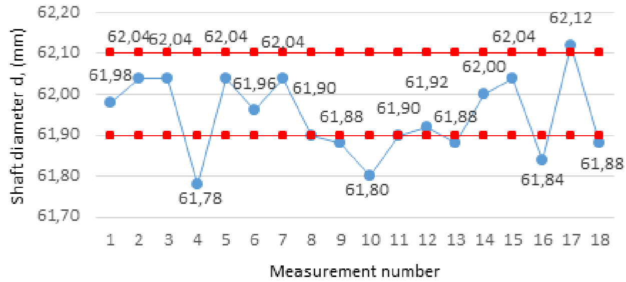

Fig. 5. Values of shaft diameter d for gear set R_d2. (H_s= 0.10mm, P_u= 75%).

TABLE III. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D2

Variable Parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10mm,	**mm**	**mm**	**mm**
P_u=75%	61.95	0.093	0.009

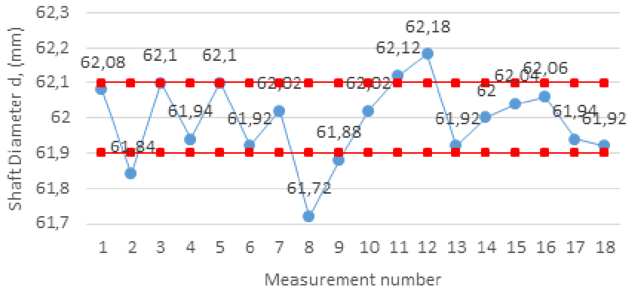

Fig. 6. Values of shaft diameter d for gear set R_d3. (H_s= 0.10mm, P_u= 50%).

TABLE IV. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D3

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10mm,	**mm**	**mm**	**mm**
P_u=50%	61.99	0.111	0.012

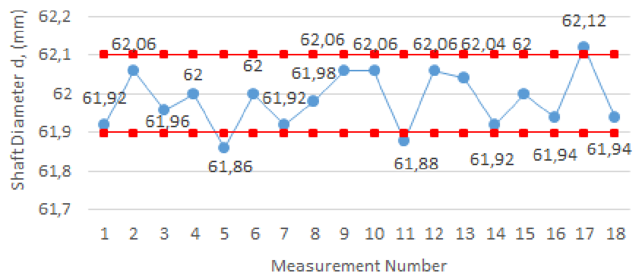

Fig. 7. Values of shaft diameter d for spur gear set R_d4. (H_s= 0.15mm, P_u= 100%).

TABLE V. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D4

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	**mm**	**mm**	**mm**
P_u=100%	61.98	0.070	0.005

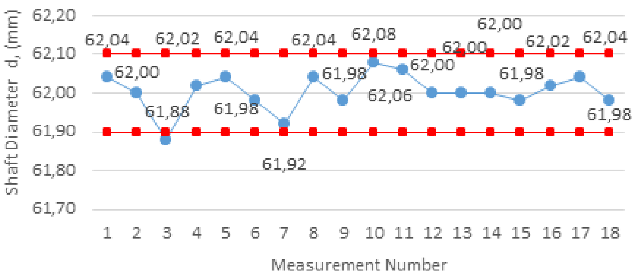

Fig. 8. Values of shaft diameter d for spur gear set R_d5. (H_s= 0.15mm, P_u= 75%).

TABLE VI. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D5

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	mm	mm	mm
P_u=75%	62	0.047	0.002

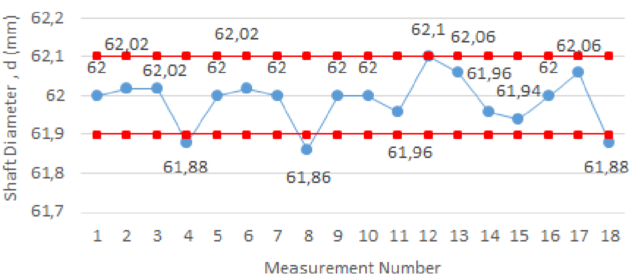

Fig. 9. Values of shaft diameter d for spur gear set R_d6. (H_s= 0.15mm, P_u= 50%).

TABLE VII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D6

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	mm	mm	mm
P_u=50%	61.99	0.063	0.004

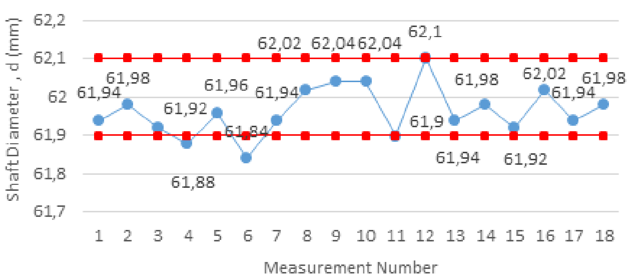

Fig. 10. Values of shaft diameter d for spur gear set R_d7. (H_s= 0.20mm, P_u= 100%).

TABLE VIII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D7

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=100%	61.96	0.062	0.004

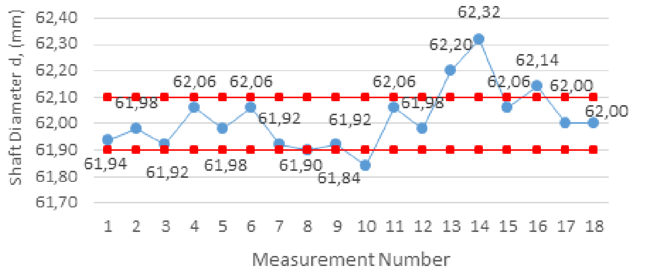

Fig. 11. Values of shaft diameter d for spur gear dințate R_d8. (H_s= 0.20mm, P_u= 75%).

TABLE IX. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D8

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=75%	62.02	0.113	0.013

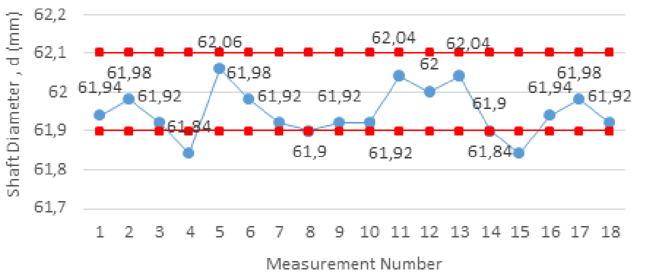

Fig. 12. Values of shaft diameter d for spur gear set R_d9. H_s= 0.20mm, P_u= 50%).

TABLE X. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D9

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=50%	61.95	0.061	0.004

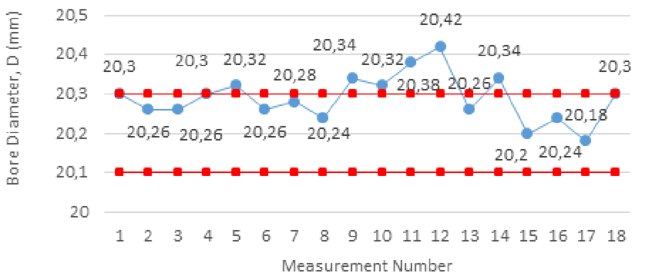

Fig. 13. Values of bore diameter D for spur gear set R_d1. (H_s= 0.10mm, P_u= 100%).

TABLE XI. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D1

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10 mm,	mm	mm	mm
P_u=100%	20.29	0.058	0.003

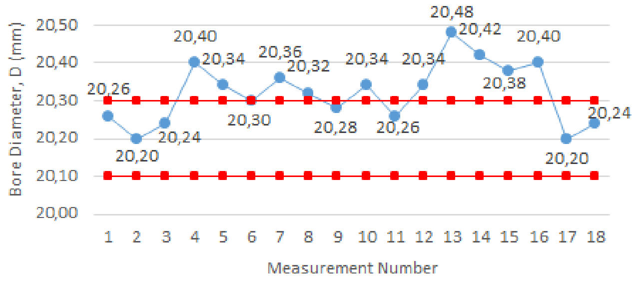

Fig. 14. Values of bore diameter D for spur gear set R_d2. (H_s= 0.10mm, P_u= 75%).

TABLE XII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D2

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10mm,	mm	mm	mm
P_u=75%	20.32	0.077	0.066

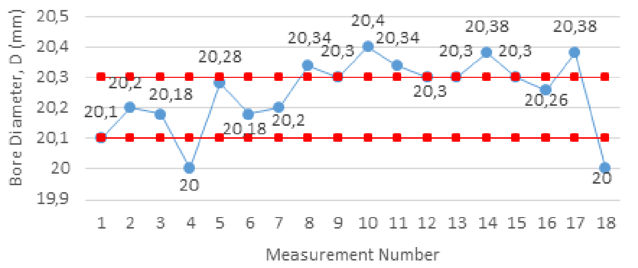

Fig. 15. Values of bore diameter D for spur gear set R_d3. (H_s= 0.10mm, P_u= 50%).

TABLE XIII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D3

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.10mm,	mm	mm	mm
P_u=50%	20.25	0.117	0.014

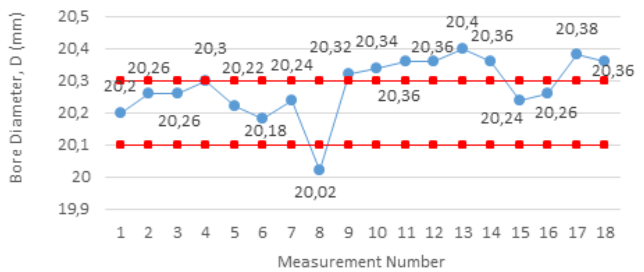

Fig. 16. Values of bore diameter D for spur gear set R_d4. (H_s= 0.15mm, P_u= 100%).

TABLE XIV. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D4

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	mm	mm	mm
P_u=100%	20.28	0.091	0.008

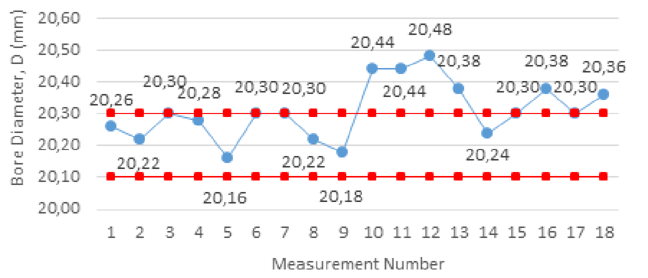

Fig. 17. Values of bore diameter D for spur gear set R_d5. (H_s= 0.15mm, P_u= 75%).

TABLE XV. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D5

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	mm	mm	mm
P_u=75%	20.31	0.088	0.008

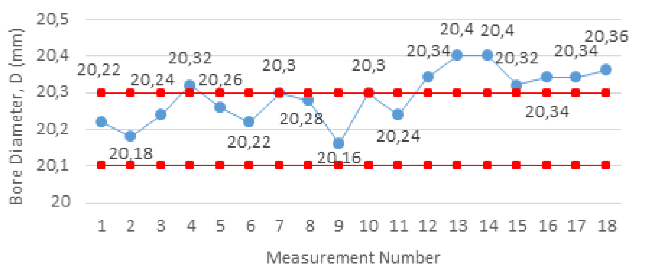

Fig. 18. Values of bore diameter D for spur gear R_d6. (H_s= 0.15mm, P_u= 50%).

TABLE XVI. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D6

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.15mm,	mm	mm	mm
P_u=50%	20.29	0.068	0.005

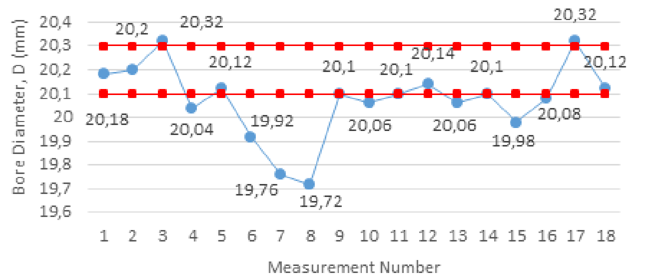

Fig. 19. Values of bore diameter D for spur gear set R_d7. (H_s= 0.20mm, P_u= 100%).

TABLE XVII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D7

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=100%	20.07	0.152	0.023

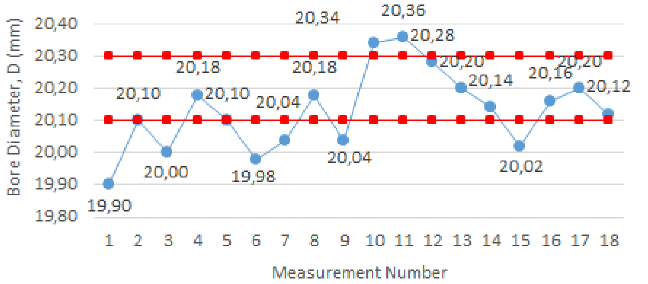

Fig. 20. Values of bore diameter D for spur gear set R_d8. (H_s= 0.20mm, P_u= 75%).

TABLE XVIII. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D8

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=75%	20.13	0.120	0.014

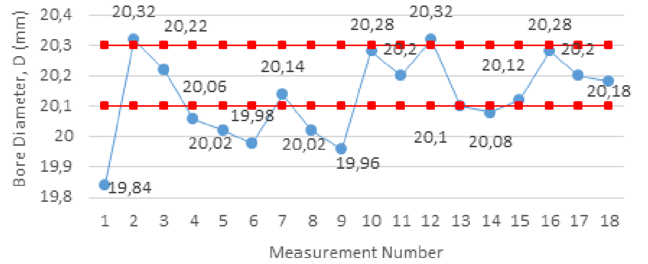

Fig. 21. Values of bore diameter D for spur gear set R_d9. (H_s= 0.20mm, P_u= 50%).

TABLE XIX. VALUES OF STATISTICAL INDICATORS FOR THE SET OF SPUR GEARS R_D9

Variable parameters	Mean $\bar{x}$	Standard Deviation σ	Dispersion σ^2
H_s= 0.20mm,	mm	mm	mm
P_u=50%	20.13	0.130	0.017

Using the values of the arithmetic means $\bar{x}$ of the shaft diameter d and of the bore diameter D (see Tables II-XIX) for each set of gears R_di (i=1...9), the graphs in Figure 22 and 23 were constructed, respectively.

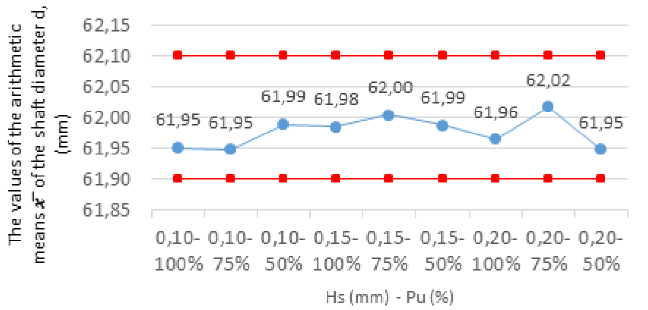

Fig. 22. Variation of the arithmetic mean values $\bar{x}$ of the shaft diameter d for each set of gears R_di (i=1...9).

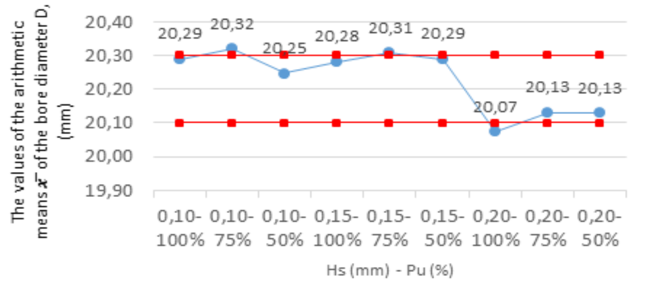

Fig. 23. Variation of the arithmetic mean values $\bar{x}$ of the bore diameter for each set of gears R_di (i= 1...9).

C. Disscusion

The study was carried out using the 162 values resulting from the measurement with the digital caliper of the shaft diameter d=62±0.1mm (see Figure 3) and the 162 values resulting from the measurement with the same instrument of the bore diameter D= 20.2±0.1 mm (see Figure 3) of the 27 cylindrical spur gears made of PLA, with modulus m= 1 and spur teeth z= 60, additively manufactured by thermoplastic extrusion (using the parameters in Table I), certify the significant influence on their dimensions of the height of the layer deposited at one pass H_s and the percentage of filling P_u.

In this context, analyzing the graphs in Figures 4-23 and the result summary in Tables II-XIX the following results are issued:

1) For Shaft Diameter d= 62±0.1mm

- The best values were obtained by measuring the set of spur gears R_d5 (Hs= 0.15mm, Pu= 75%), the calculated mean being $\bar{x}$= 62mm and dispersion σ^2= 0.002 (see Figure 9 and Table VI).
- The largest deviations were obtained in the measurement of the spur gear set R_d2 (Hs= 0.10mm, Pu= 75%), the calculated mean average being $\bar{x}$= 61.95mm, and dispersion σ^2= 0.0087 (see Figure 5 and Table III);
- 100% of the values obtained in the measurement of the spur gear set R_di (i= 1...9) are within the tolerance of ±0.10mm, the best values being obtained for 3D printing with the height of the deposited layer at a pitch Hs= 0.15mm (see Figure 22).

2) For Bore Diameter D= 20.2±0.1mm:

- The best values were obtained in the measurement of the spur gear set R_d3 (Hs= 0.10mm, Pu= 50%), the calculated mean being $\bar{x}$= 20.25mm, and dispersion σ^2= 0.014 (see Figure 15 and Table XIII).
- The largest deviations were obtained in the measurement of the spur gear set R_d7 (Hs= 0.20mm, Pu = 100%), the calculated average being $\bar{x}$ = 20.07mm, and dispersion σ^2= 0.023 (see Figure 19 and Table XVII).
- Only 66.6% of the values obtained in the measurement of the spur gear set R_di (i= 1...9) fall within the tolerance of ±0.10mm, very close to the upper and lower limits (see Figure 23).

IV. CONCLUSIONS

The current paper presents the results of a theoretical-experimental study on the influence of FDM parameters (height of the deposited layer at one pass H_s and percentage of filling P_u) on the dimensions (shaft diameter d and bore diameter D) of cylindrical spur gears made of PLA. Cylindrical spur gears were printed on Creality CR-X 3D printer using PLA filament - Verbatim brand.

Regarding the shaft diameter d, all values obtained in the measurement of FDM 3D printed spur gears are within the required tolerance of ±0.10 mm.

Regarding the bore diameter D, one third of the measued values were outside the tolerance limits. The difference between the extreme values of the arithmetic mean is 0.25mm.

The theoretical-experimental study demonstrates that of the two FDM parameters analyzed, the P_u filling percentage has a greater influence on the dimensional accuracy of spur gears made of PLA.

The results of the study are useful for optimizing FDM parameters for additive manufacturing of PLA spur gears by thermoplastic extrusion within specified dimensional tolerances. The study can be extrapolated to other types of materials used in additive manufacturing technologies.

REFERENCES

[1] I. Buj-Corral and E. E. Zayas-Figueras, "Comparative study about dimensional accuracy and form errors of FFF printed spur gears using PLA and Nylon," *Polymer Testing*, vol. 117, Jan. 2023, Art. no. 107862, https://doi.org/10.1016/j.polymertesting.2022.107862.

[2] M. M. Hanon, L. Zsidai, and Q. Ma, "Accuracy investigation of 3D printed PLA with various process parameters and different colors," *Materials Today: Proceedings*, vol. 42, pp. 3089–3096, Jan. 2021, https://doi.org/10.1016/j.matpr.2020.12.1246.

[3] D.G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Theoretical and Experimental Research on the Influence of FDM Parameters on Tensile Strength and Hardness of Parts Made of Polylactic Acid", *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7458–7463, Aug. 2021, https://doi.org/10.48084/etasr.4311.

[4] D. G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Statistical Approach of the Flexural Strength of PLA and ABS 3D Printed Parts," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8248–8252, Apr. 2022, https://doi.org/10.48084/etasr.4739.

[5] D. G. Zisopol, I. Nae, and A. I. Portoaca, "Compression Behavior of FFF Printed Parts Obtained by Varying Layer Height and Infill Percentage," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9747–9751, Dec. 2022, https://doi.org/10.48084/etasr.5488.

[6] D. G. Zisopol, D. V. Iacob, and A. I. Portoaca, "A Theoretical-Experimental Study of the Influence of FDM Parameters on PLA Spur Gear Stiffness," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9329–9335, Oct. 2022, https://doi.org/10.48084/etasr.5183.

[7] "3D CAD Design Software," *SOLIDWORKS*. https://www.solidworks.com/home-page-2021.

[8] "3D printing software of Creality Cloud," *Creality Cloud*. https://www.crealitycloud.com/software-firmware/software?type=8.

[9] D. G. Zisopol, A. I. Portoaca, I. Nae, and I. Ramadan, "A Comparative Analysis of the Mechanical Properties of Annealed PLA," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8978–8981, Aug. 2022, https://doi.org/10.48084/etasr.5123.

[10] A. Portoaca, I. Nae, D. G. Zisopol, and I. Ramadan, "Studies on the influence of FFF parameters on the tensile properties of samples made of ABS," *IOP Conference Series: Materials Science and Engineering*, vol. 1235, no. 1, Nov. 2022, Art. no. 012008, https://doi.org/10.1088/1757-899X/1235/1/012008.

[11] H. S. Park, N. H. Tran, V. T. Hoang, and V. H. Bui, "Development of a Prediction System for 3D Printed Part Deformation," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9450–9457, Dec. 2022, https://doi.org/10.48084/etasr.5257.

[12] M. Minescu and D. Zisopol, *Sudarea ţevilor şi fitingurilor din polietilenă de înaltă densitate (HDPE Pipe & Fittings Welding)*. Ploiesti, Romania: UPG Ploieşti Publishing House, 2021.

[13] D. Zisopol and A. Dumitrescu, *Ecotehnologie. Studii de caz*. Ploiesti, Romania: UPG Ploieşti Publishing House, 2021.

[14] D. G. Zisopol, A. Dumitrescu, C. N. Trifan, *Ecotehnologie: Noţiuni teoretice, aplicaţii şi studii de caz*, Ploiesti, Romania: UPG Ploieşti Publishing House, 2010.

[15] D. G. Zisopol, M. J. Săvulescu, *Bazele tehnologiei*, Ploiesti, Romania: UPG Ploieşti Publishing House, 2003.

[16] D. G. Zisopol, *Tehnologii industriale şi de construcţii. Aplicaţii practice şi studii de caz*, Ploiesti, Romania: UPG Ploieşti Publishing House, 2003.

[17] M. J. Săvulescu, D. G. Zisopol, *Tehnologii industriale şi de construcţii*, Ploiesti, Romania: UPG Ploieşti Publishing House, 2002.

[18] D. G. Zisopol, *Ingineria valorii*, Ploiesti, Romania: UPG Ploieşti Publishing House, 2004.

[19] T. A. Cojoianu, "Studiu comparativ privind influența parametrilor tehnologiei de fabricație aditivă prin extrudarea PLA și ABS asupra abaterilor dimensionale ale roților dințate cilindrice și rigidității angrenării acestora," M.S. thesis, Petroleum-Gas University, Ploiesti, Romania, 2022.

[20] D. V. Iacob, "Măsurarea rigidității angrenării roților dințate fabricate din PLA, folosite la antrenarea cuțitului unității de tăiere a mașinii pentru fabricarea corpurilor radiatoarelor auto", M.S. thesis, Petroleum-Gas University, Ploiesti, Romania, 2022.