ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20240422144655

Preliminary communication
Received: 2024-04-22, Accepted: 2024-04-24

Analysis of the Impact of Geometry Modifications on the Fit of Splined Shaft Connections Manufactured Using Selected AM Methods

Grzegorz Budzik, Tomasz Dziubek*, Małgorzata Gontarz, Bartłomiej Sobolewski, Małgorzata Zaborniak

Abstract: Broadly, understood additive manufacturing techniques expand the spectrum of production of machine parts that are used in various types of devices. However, the requirements to ensure dimensional and shape accuracy require the determination of appropriate material allowances or clearances to enable correct assembly. For the above reasons, the study presents an analysis of the impact of the assumed geometry modifications on the possibility of assembling a splined connection manufactured using selected AM techniques. The work focused on the analysis of changes in geometry resulting from the technology used. Using the Atos II Triple Scan optical measurement system and Gom Inspect software, the possibility of installation was determined for four variants of the splined shaft connection geometry, resulting from the technologies used.

Keywords: 3D Printing; CAx systems; coordinate measurements method; coordinate optical measurements; quality control

1 INTRODUCTION

Geometric accuracy is one of the fundamental qualifiers for the correctness of manufacturing processes for machine and device parts. It is the result of many components constituting the overall effect of the production process. In order to provide it, it is necessary to integrate CAD / CAM / RP / CMM (Computer Aided Design / Computer Aided Manufacturing / Rapid Prototyping / Coordinate Measuring Machine) systems, which create a holistic environment for the production of products, regardless of the field of application [1].

Determining the accuracy of manufacturing parts with complex geometry, produced in the RP process, can be carried out using coordinate measuring techniques. The integration of computer-aided design (CAD), manufacturing (CAM / RP) systems and coordinate measuring methods (CMM) allows for a significant acceleration of the production process of high-quality machine parts. This is especially important in the case of manufacturing assembly elements, for which the dimensions responsible for their correct assembly are extremely important [2, 3].

The topic covered in this study aims to illustrate problems and phenomena affecting the accuracy of splined connections manufactured using selected additive techniques. The task undertaken in the research work resulted from the lack of reliable information regarding the size of geometry deviations resulting from the manufacturing techniques and materials used [4, 5]. The information provided by manufacturers of materials as well as 3D printers, does not offer a complete picture of geometry deformations resulting from the manufacturing method used. Moreover, there is a lack of studies containing guidelines for predicting appropriate assembly clearances when designing splined connections. This is an important issue because these connections are indirectly responsible for the correct operation of, for example, gear transmissions [6]. The research performed concerned the analysis of spline connections manufactured using Fused Filament Fabrication (FFF) and PolyJet technologies [7-9]. PLA and RGD720 photopolymer resin materials were used for the manufacturing processes. Research models were developed for a gear mounted on a shaft.

In the conducted research, considerations regarding the analysis of the accuracy of the gear ring geometry were omitted. The interpretation of the measurement results focuses on the impact of the size of the designed clearances of the splined connection on its correctness or the possibility of its assembly. The presented results were based on measurements of a series of 5 samples with the same geometry for each defined clearance size and manufacturing method. Due to the scope of the study, selected representative analyzes are presented.

2 RESEARCH ISSUES

The objective of this study was to assess the impact of the size of assembly clearances, predetermined at the stage of modeling the geometry of a spline connection dedicated to manufacturing using selected incremental manufacturing techniques. Due to the geometry deformations inherent during production, it was imperative to investigate the influence of base geometry shape on subsequent correct assembly of the splined connection.

The scope of the study encompasses:

- Conducting the process of modeling the geometry of splines with nominal geometry and with assumed assembly clearances (Fig. 1).
- Production of 5 series of prototypes for each designed geometry and manufacturing method (Fig. 2) [10, 11].
- Carrying out post-processing to properly prepare research samples.
- Carrying out measurement processes and analyzing model accuracy using the GOM Inspect software (Fig. 3, 4).
- Comparative analysis of the results obtained in relation to real research models, considering nominal geometry without geometric correction.

The design work carried out included the development of the geometry of a splined connection, the geometry of which is the same for the hole and the shaft. Then, manufacturing clearances were assumed at the level of 0.1

mm, 0.15 mm and 0.2 mm, respectively, which were taken into account on the designed shaft (Fig. 1). The gear wheel was treated according to the principles of a constant hole, and thus the hole parameters were constant.

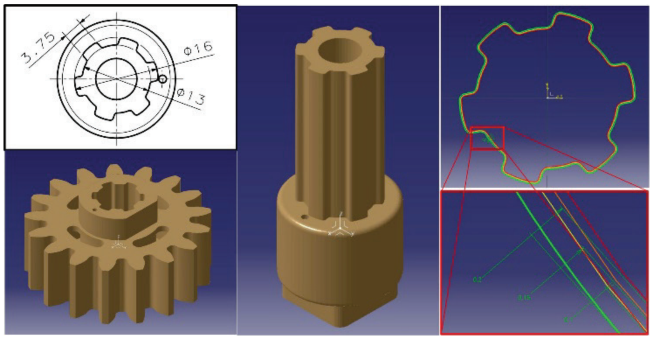

Figure 1 STL models of test bodies

Using FFF and PolyJet additive manufacturing methods, a series of 5 test models of gears and shafts for each designed geometry were manufactured using the Prusa MK3 device and 3D Objet 350 Connex [12].

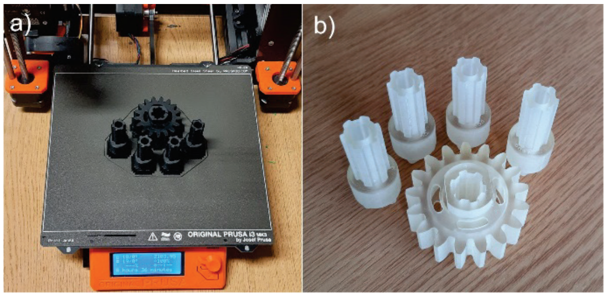

Figure 2 Research prototypes produced in technology: a) FFF, b) PolyJet

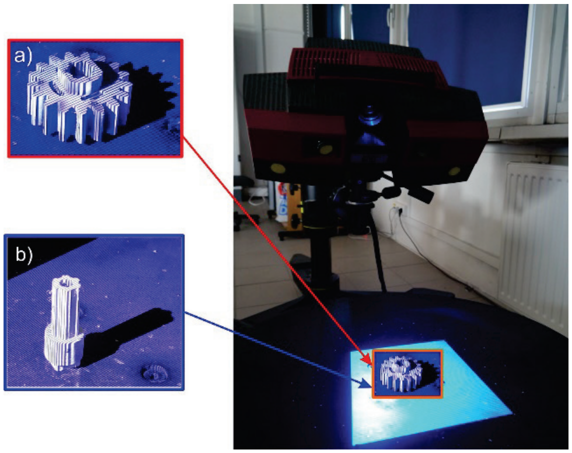

Figure 3 Measurement using the optical 3D scanner Atos II Triple Scan: a) Gear, b) shaft

The measurement processes were conducted using the Atos II Triple Scan optical 3D scanner (Fig. 3, 4). Consequently, in order to be able to digitize the contact surface of the detail with the measuring table and the geometry located outside the camera observation area, it was necessary to measure it in two independent measurement series. The measurement process was configured in such a way that each of the two series was carried out for the position of the part placed in a given plane of the table as well as in a plane rotated by 180 degrees [13]. However, this required the arrangement of reference points such that at least three of them are visible in both measurement series to enable individual geometries to be aligned [14].

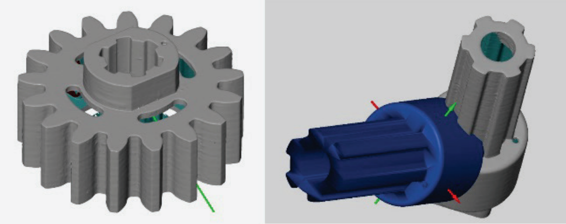

Figure 4 Measurement data

3 EXPERIMENTAL AND RESULTS

The Atos II Triple Scan optical coordinate scanner software enables analysis of the accuracy of machine parts, presenting results both quantitatively and through colorful deviation maps. The use of an optical 3D scanner and the methodology developed for measuring gears [14] is adaptable to other geometrically complex machine parts manufactured using additive techniques. The software ensures metrologically precise measurement of characteristic geometric features determining measured geometry accuracy.

By overlaying the surface geometry obtained through optical scanning onto the reference 3D-CAD model, a global analysis was conducted to visually assess the impact of spline geometry modification on dimensional shape changes resulting from manufacturing technology and materials used. Additionally, geometry analyses in sections normal to the axis were presented for individual cases. These tests were conducted for all samples analyzed in relation to the nominal geometry (Fig. 5-24). The deviation maps provided in the drawings offer information about their distribution both visually and quantitatively, facilitating comparison with the nominal model for better analysis.

3.1 Analysis of the Geometry of Prototypes Manufactured using PolyJet Technology

First, prototypes made using PolyJet technology were analyzed. The geometry of the gear bore was used as the assembly reference base. It was in relation to it that analyzes of the possibility of correct installation were carried out. According to the tests conducted, the gear wheel hole was reduced by +0.03 to +0.13 mm (Fig. 5, 6). It depends on the complexity of the geometry and its location on the manufactured object. Additionally, the type of material and the degree of its flow have an influence. To visualize geometry deformation better, analyses were performed in three sections. However, due to space limitations, only one example is presented, depicting deviation maps in half the width of the opening (Fig. 6), with similar values observed in other cross-sections. Preliminary information obtained from the analysis indicates the inability to achieve correct connection for models without geometry correction.

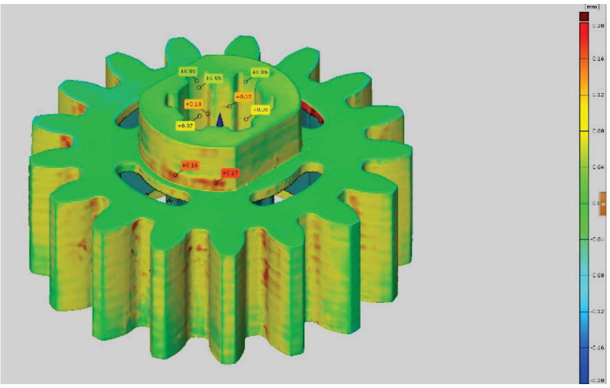

Figure 5 Global analysis of the gear geometry – PolyJet nominal model

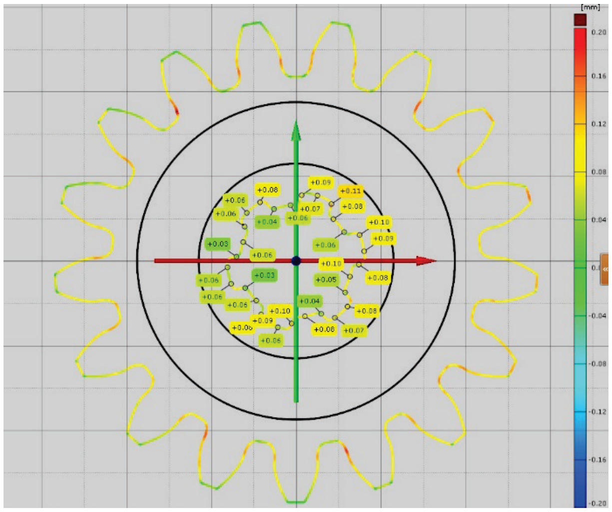

Figure 6 Cross-sectional analysis of the gear model– PolyJet nominal model

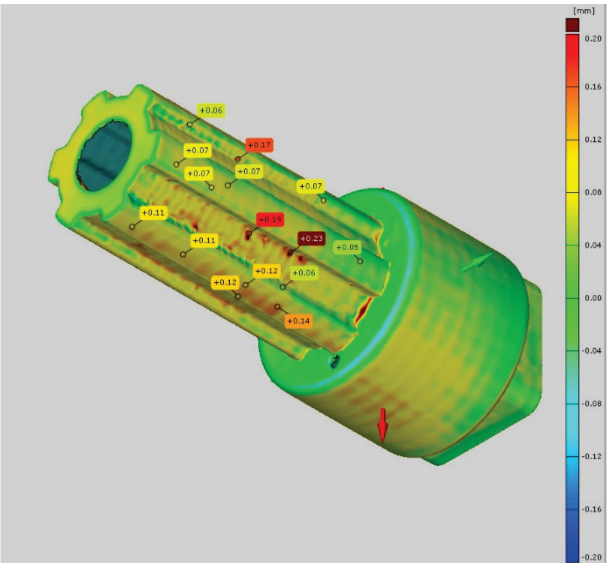

Figure 7 Global analysis of the shaft geometry – PolyJet nominal model

In order to determine the values of clearances necessary for the correct assembly of the splined connection, the geometry of individual shafts was analyzed. Initially, global surface deviation maps were prepared for each geometry (nominal and offsets of 0.1 mm, 0.15 mm, 0.2 mm) (Fig. 7-10). These revealed that only increasing clearance to 0.15 mm enabled connection assembly (Fig. 9).

The deviation values for the nominal geometry and an offset of 0.1 mm do not ensure connection mounting feasibility. Modifying geometry by 0.2 mm (Fig. 10) results in excessive play, leading to incorrect assembly.

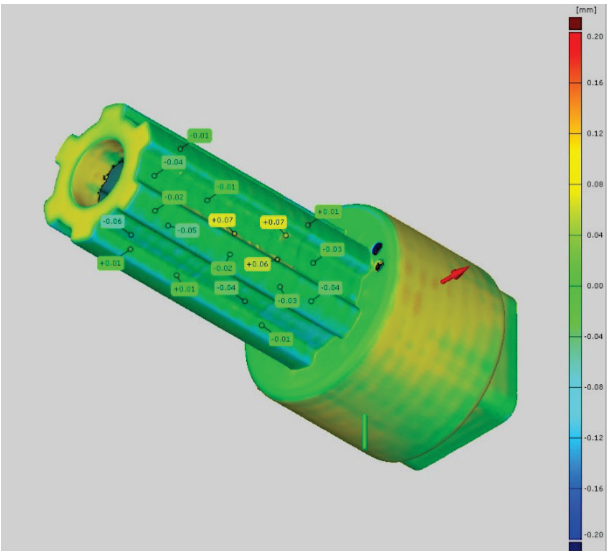

Figure 8 Global analysis of the shaft geometry – PolyJet offset 0.1 mm

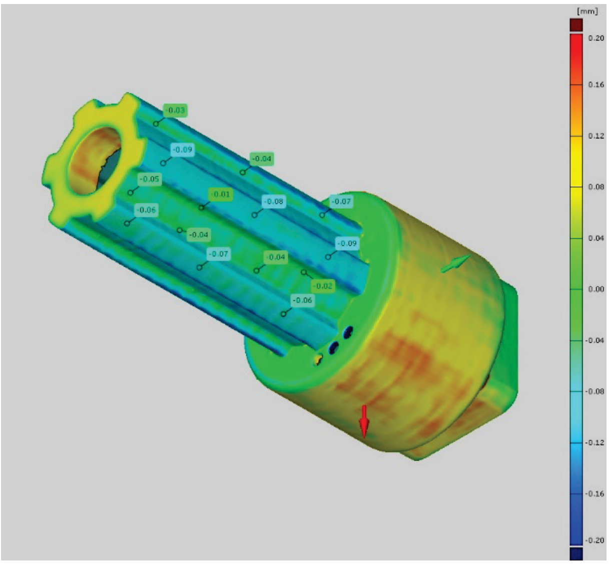

Figure 9 Global analysis of the shaft geometry – PolyJet offset 0.15 mm

In order to detail the analyzes performed, additional detailed maps of deviations were prepared in the form of inspection cross-sections (Fig. 11-14). This article includes representative analyzes performed at half the length of the shaft. In total, three cross-sections along the entire length of each prototype were made, and the results obtained are consistent with those presented.

As a result of comparing sample analyzes performed for individual research models, it is possible to observe the occurrence of geometry changes confirming and specifying the global analyzes (Figs. 9-11). The distributions of deviations presented in the figures below do not require detailed commentary, as they clearly illustrate the differences between the individual cases examined.

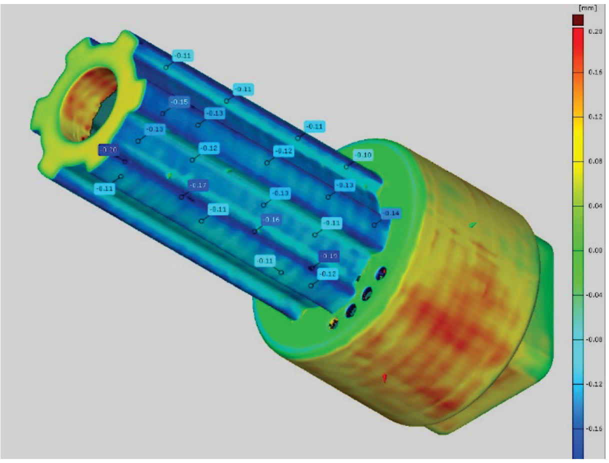

Figure 10 Global analysis of the shaft geometry – PolyJet offset 0.2 mm

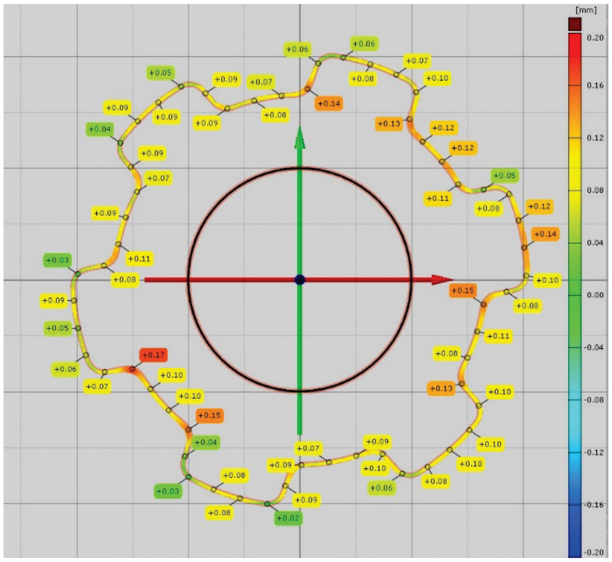

Figure 11 Cross-sectional analysis of the shaft model – PolyJet nominal model

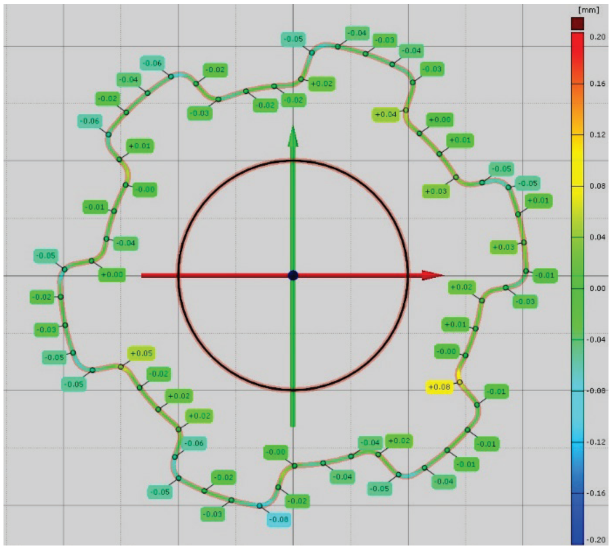

Figure 12 Cross-sectional analysis of the shaft model – PolyJet offset 0.1 mm

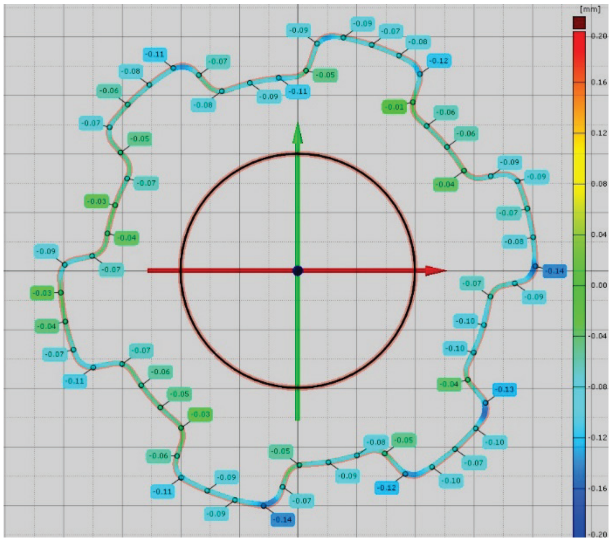

Figure 13 Cross-sectional analysis of the shaft model – PolyJet offset 0.15 mm

Additional analyzes in the form of inspection sections showed that a geometry correction of 0.15 mm ensures correct assembly of the connection. As depicted in Fig. 13, the geometry deviations in the range –0.14 to –0.03 mm provide compensation for hole production errors. Thanks to this, preliminary analyzes in the form of global deviation maps were confirmed. Additionally, this was confirmed by tests on real models. The result was the inability to assemble the connection for nominal geometries as well as models made with an offset of 0.1 mm, and excessive clearance for prototypes made with an offset of 0.2 mm.

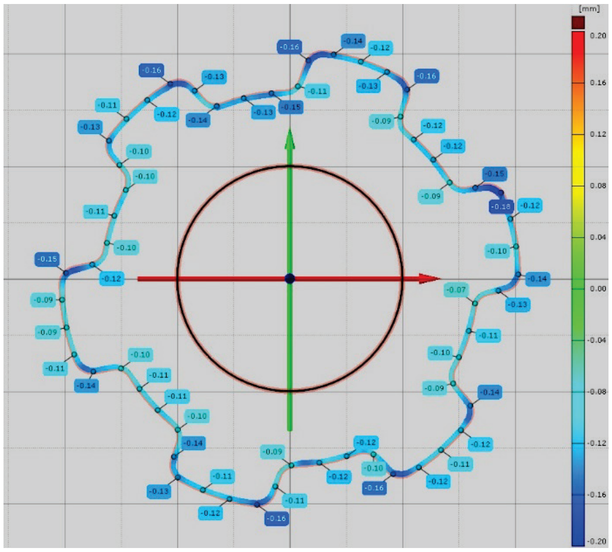

Figure 14 Cross-sectional analysis of the shaft model – PolyJet offset 0.2 mm

3.2 Analysis of the Geometry of Prototypes Manufactured using FFF Technology

Similar to prototypes manufactured using PolyJet technology, analyses were conducted for models produced using the FFF method. Analyzes performed for the geometry of the gear wheel hole showed geometry deviations ranging from –0.14 to +0.1 mm (Fig. 15, 16). These results suggest the occurrence of partial shrinkage for the material and manufacturing technology employed.

To determine necessary clearance values for correct splined connection assembly, individual shaft geometries were analyzed. Initially, global surface deviation maps were generated for each geometry (nominal and offsets of 0.1 mm, 0.15 mm, 0.2 mm) (Fig. 17-20). The findings indicated that increasing clearance to 0.1 mm might facilitate connection assembly (Fig. 18).

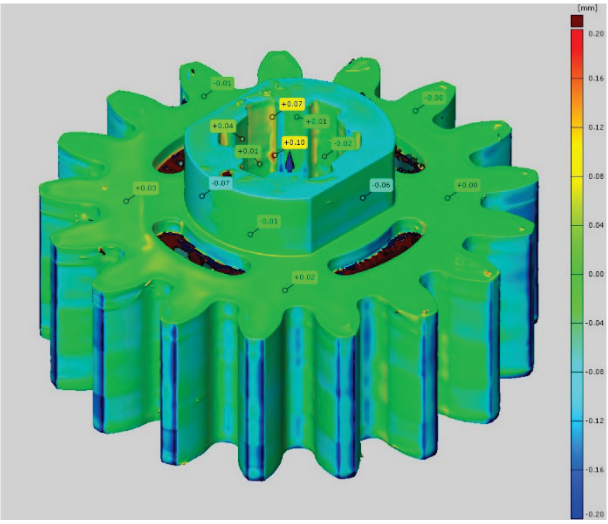

Figure 15 Global analysis of the gear geometry – FFF nominal model

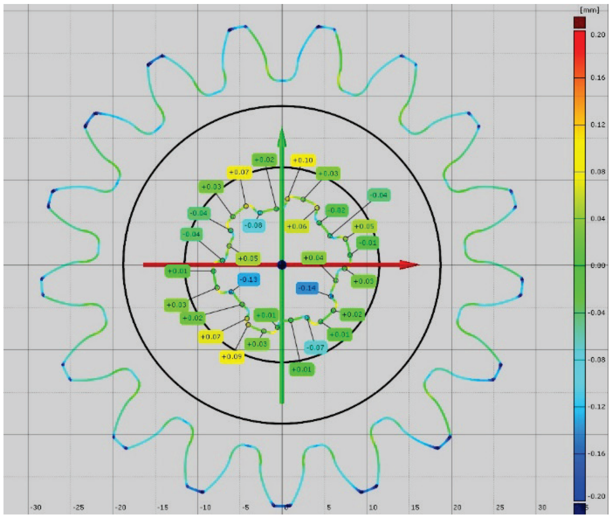

Figure 16 Cross-sectional analysis of the gear model – FFF nominal model

In this case, only deviation values for nominal geometry do not ensure the possibility of mounting the connection. With geometry modifications of 0.15 mm and 0.2 mm (Fig. 19, 20), connections exhibit excessive looseness, resulting in incorrect assembly.

For detailed analyses, additional deviation maps were prepared in the form of inspection cross-sections (Fig. 21-24).

Comparing sample analyses for individual research models reveals geometry changes, confirming and specifying global analyses (Figs. 17-20). Similar to previous analyses, deviation distributions in the figures below do not require detailed commentary, as they clearly illustrate differences between examined cases.

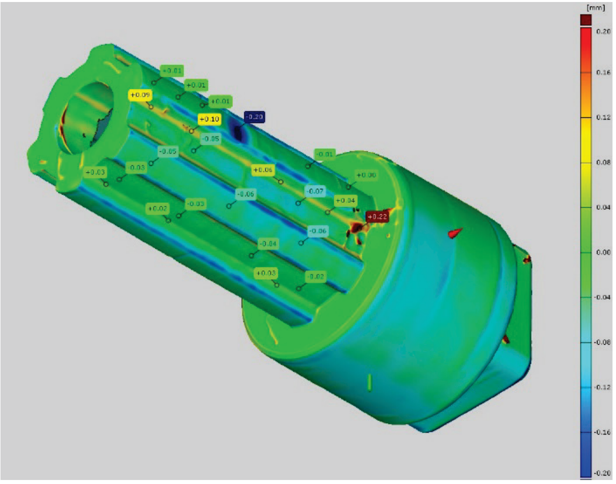

Figure 17 Global analysis of the shaft geometry – FFF nominal model

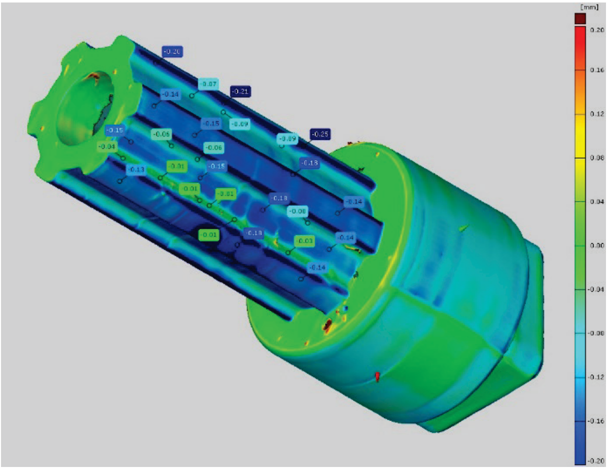

Figure 18 Global analysis of the shaft geometry – FFF offset 0.1 mm

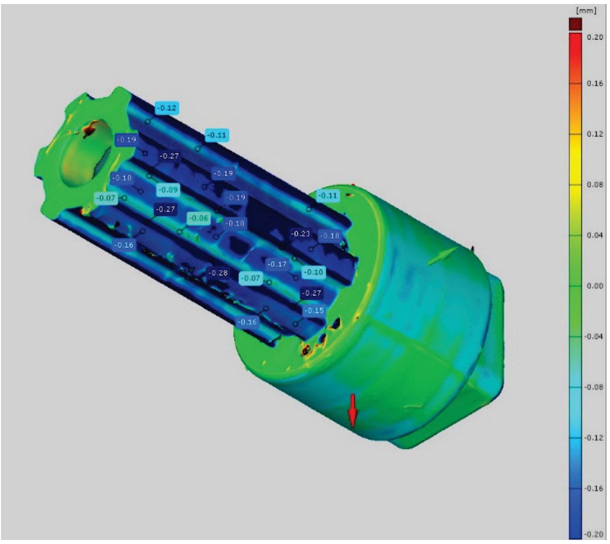

Figure 19 Global analysis of the shaft geometry – FFF offset 0.15 mm

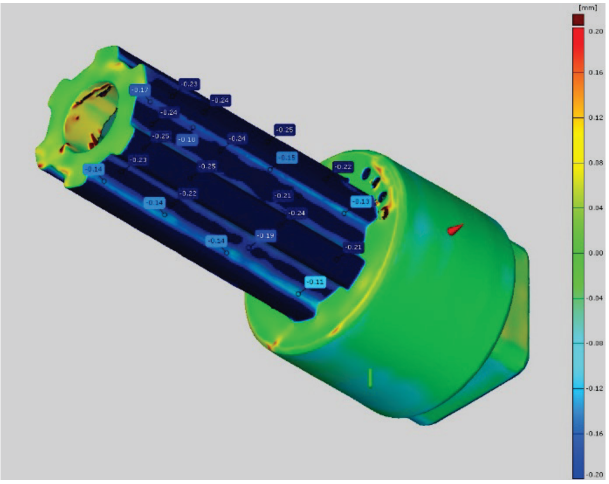

Figure 20 Global analysis of the shaft geometry – FFF offset 0.2 mm

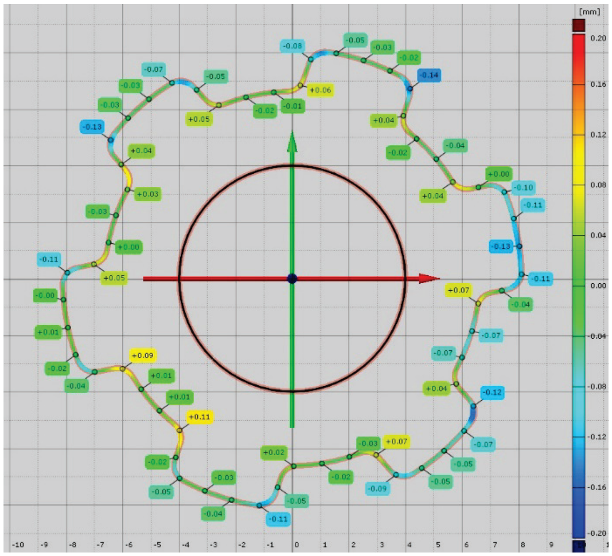

Figure 21 Cross-sectional analysis of the shaft model – FFF nominal model

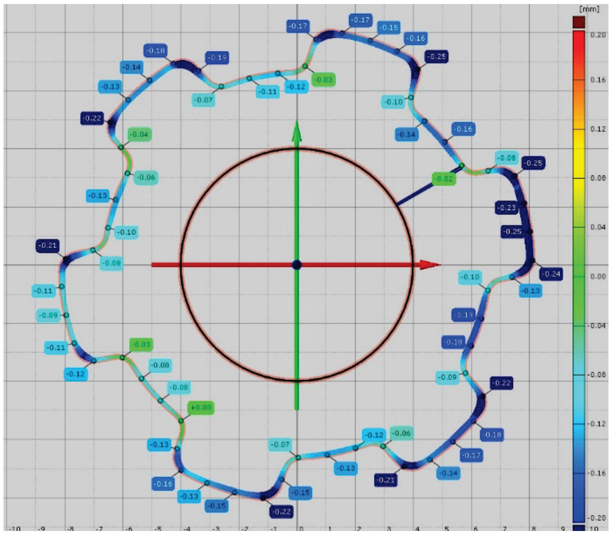

Figure 22 Cross-sectional analysis of the shaft model – FFF offset 0.1 mm

Further analyses through inspection sections indicated that a 0.1 mm geometry correction ensures correct connection assembly. As depicted in Fig. 22, geometry deviations ranging from –0.25 to –0.02 mm compensate for hole production errors, confirming preliminary analyses through global deviation maps. Additionally, this was confirmed by tests on real models. The result was the inability to assemble the connection for nominal geometries and excessive clearance for prototypes manufactured with offsets of 0.15 mm and 0.2 mm.

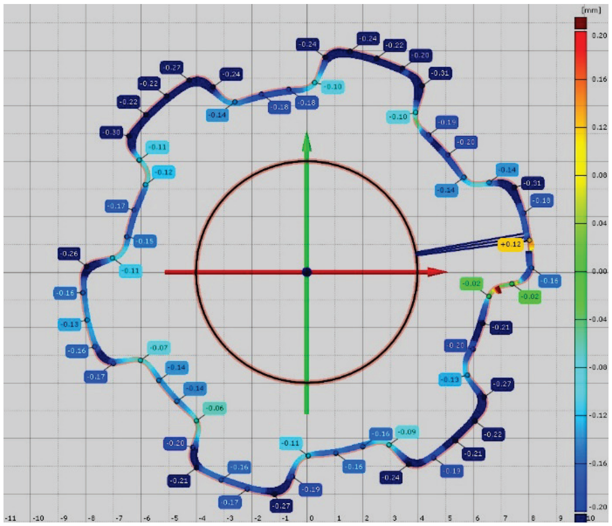

Figure 23 Cross-sectional analysis of the shaft model – FFF offset 0.15 mm

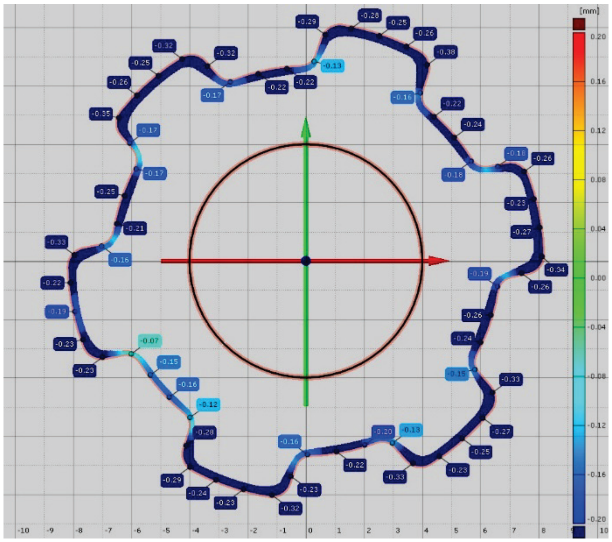

Figure 24 Cross-sectional analysis of the shaft model – FFF offset 0.2 mm

4 CONCLUSIONS

The methodology outlined in this article facilitates a swift and efficient assessment of the impact of modifying the geometry of a spline connection on its assembly possibilities. The results of the analyzes were presented, taking into account the selected manufacturing technologies and materials used. Through comprehensive analyses and inspection cross-sections, any geometric irregularities were graphically visualized, allowing for the determination of their deformation extent.

Based on the conducted tests and the results presented, it is evident that the outcomes vary for the designed geometry, contingent upon the manufacturing technique and material employed. In the case of Fused Filament Fabrication (FFF) technology using PLA material, modifying the geometry by a 0.1 mm offset was sufficient to ensure proper assembly, as depicted by the deviations illustrated in Figs. 16 and 22. This resulting connection guarantees correct assembly with slight perceptible resistance, validated through physical model testing (Fig. 25).

Figure 25 Checking the correctness of the prototypes geometry made using the FFF method

Regarding the results pertaining to PolyJet technology with RGD720 material, achieving correct assembly necessitated modifying the geometry by a 0.15 mm offset, demonstrated by the deviations shown in Figs. 6 and 13. Similarly to PLA, the connection thus obtained ensures proper assembly with slight perceptible resistance, as confirmed through physical model testing (Fig. 26).

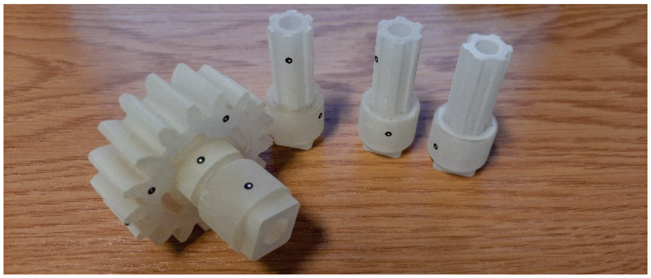

Figure 26 Checking the correctness of the prototypes geometry made using the PolyJet method

The research, analyses, and tests conducted on physical models demonstrate consistent findings. However, it should be noted that geometry deviations increased for prototypes manufactured using PolyJet technology. In the case of FFF technology, increasing the offset of the shaft spline profile by 0.05 mm was necessary for proper connection assembly.

The tests and examinations conducted exhibited repeatability and yielded convergent results across all samples. Building upon this foundation, further research endeavors are planned to explore various manufacturing clearance sizes across a broader range of spline connection dimensions.

5 REFERENCES

[1] Dziubek, T., Budzik, G., Kawalec, A., Dębski, M., Turek, P., Oleksy, M., Paszkiewicz, A., Poliński, P., Kochmański, Ł., Kiełbicki, M., Józwik, J., Kuric, I. & Cebulski, J. (2020). Strength of threaded connections additively produced from polymeric materials. *Polimery, 67*(6), 261-270. https://doi.org/10.14314/polimery.2022.6.4

[2] Budzik, G., Woźniak, J., Paszkiewicz, A., Przeszłowski, Ł., Dziubek, T. & Dębski, M. (2021). Methodology for the quality control process of additive manufacturing products made of polymer materials. *Materials, 14*, 2202. https://doi.org/10.3390/ma14092202

[3] Wieczorowski, M., Budzik, G., Gapiński, B. & Dziubek, T. (2022). Determining the Assumptions for the Selection of Measurement Methods for Products Manufactured with Incremental Methods. *Tehnicki Glasnik, 16*(2), 258-263. https://doi.org/10.31803/tg-20220408113840

[4] Gibson, I., Rosen, D., Stucker, B. & Khorasani, M. (2021). Materials for additive manufacturing. *Additive Manufacturing Technologies,* 379-428. https://doi.org/10.1007/978-3-030-56127-7_14

[5] Ian, C., Olaf, D., Joseph, K., Noah, M. & Terry, W. (2021). Wohlers Report 2019: Additive Manufacturing and 3D Printing State of the Industry. van Rensburg, J., Ed., Wohlers Associates, Inc.: Fort Collins, CO, USA.

[6] Zajdel, M., Pisula, J., Sobolewski, B., Sanocki, T., Majcherczyk, H., Budzik, G. & Oleksy, M. (2022). Geometrical accuracy of injection-molded composite gears. *Polimery, 67*(7-8), 324-336. https://doi.org/10.14314/polimery.2022.7.5

[7] Budzik, G., Dziubek, T., Przeszłowski, Ł. P., Sobolewski, B., Dębski, M. & Gontarz, M. E. (2023). Study of unidirectional torsion of samples with different internal structures manufactured in the MEX process. *Rapid Prototyping Journal, 29*(8), 1604-1619. https://doi.org/10.1108/RPJ-09-2022-0332

[8] Buswell, R. A., Leal de Silva, W. R., Jones, S. Z. & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research, 112*, 37-49. https://doi.org/10.1016/J.CEMCONRES.2018.05.006

[9] Fuwen, H., Mikolajczyk, T., Pimenov, D. Y. & Gupta, M. K. (2021). Extrusion-based 3D printing of ceramic pastes: Mathematical modelling and in situ shaping retention approach. *Materials, 14*, 1137. https://doi.org/10.3390/MA14051137

[10] ISO/ASTM52921-13 (2019) Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies.

[11] ISO/ASTM52915-20 Specification for Additive Manufacturing File Format (AMF) Version1.2.

[12] Turner, B. N. & Gold, S. A. (2015). Are view of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyp. J., 21*, 250-261. https://doi.org/10.1108/RPJ-02-2013-0017

[13] Dziubek, T. (2018). Application of coordination measuring methods for assessing the performance properties of polymer gears. *Polimery, 63*(1), 49-52. https://doi.org/10.14314/polimery.2018.1.8

[14] Dziubek, T. & Oleksy, M. (2017). Application of ATOS II optical system in the techniques of rapid prototyping of epoxy resin-based gear models. *Polimery, 62*(1), 44-51. https://doi.org/10.14314/polimery.2017.044

Authors' contacts:

Grzegorz Budzik, Prof. PhD, DSc, Eng.
Rzeszów University of Technology,
Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
gbudzik@prz.edu.pl

Tomasz Dziubek, PhD, DSc. Eng. Associate Prof.
(Corresponding author)
Rzeszów University of Technology,
Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
tdziubek@prz.edu.pl

Małgorzata Gontarz, MSc, Eng.
Rzeszów University of Technology,
Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
m.gontarz@prz.edu.pl

Bartłomiej Sobolewski, DSc. Eng.
Rzeszów University of Technology,
Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
b_sobolewski@prz.edu.pl

Małgorzata Zaborniak, DSc. Eng.
Rzeszów University of Technology,
Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
mzab@prz.edu.pl