Comparative accuracy analysis of continuous fiber composite printers: Coextrusion vs. dual-nozzle technology

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Abstract. Material Extrusion (MEX) technology for continuous fiber reinforced thermoplastic composites (CFRTCs) is based on the extrusion of a continuous fiber to create three-dimensional composite objects layer by layer. This technology explores three distinct methods: pre-impregnated filament, dual-nozzle, and coextrusion. The goal of this paper is to compare two printers, one using the dual nozzle technology and another relying on coextrusion. The first printer, Mark Two of Markforged, is based on dual-nozzle technology. The second printer, the Anisoprint Composer A4, stands out for its coextrusion method. Three adaptive Geometrical Benchmark Test Artifacts (GBTA), proposed by Spitaels et al. were fabricated with each printer to determine their dimensional performances. Measurements are taken using a Coordinate Measuring Machine (CMM) Wenzel LH 54. The overall deviation results of the two printers are around the IT14 standard. Deviations for measurements between 1 and 10 mm are greater compared to dimensions exceeding 10 mm, averaging around IT 12. Along the Y-axis, Markforged shows smaller deviations, attributed to its smaller print bed dimension compared to Anisoprint. Additionally, Z-axis deviations are lower than those along other axes, suggesting both printers have better precision in vertical build plate movement compared to print head movement. Notably, significant deviations are observed at the center of the GBTA in comparison to the other three axes (X, Y, and Z) for both printers.

Introduction

Additive Manufacturing (AM) processes are defined as technologies capable of "assembling materials to fabricate objects from 3D model data, typically layer by layer, as opposed to subtractive or formative manufacturing methodologies" following the ASTM D638 [1]. Currently, AM processes are a fairly advanced research topic. They have the potential to manufacture parts with complex geometric shapes with minimal material waste [2]. With this method, it is possible to produce parts with a design impossible to achieve by conventional manufacturing methods. This process is becoming increasingly popular and, as a result, is interesting for a wide range of applications such as aerospace, automotive, medicine, and biofabrication [2]. AM relies on several technologies. The one discussed in this article is Material Extrusion (MEX). It is an additive manufacturing method that uses the fusion and extrusion of material to create 3D objects. The process itself is called Fused Deposition Modeling (FDM) and it consists of the creation of a 3D model using computer-aided design software, followed by a slicing step that divides the model into thin layers. At the 3D printer, a filament of thermoplastic material, possibly accompanied by fibers, is heated up and extruded through a movable nozzle. The nozzle deposits the melted material layer by layer, following the coordinates of the 3D model. The extruded material quickly solidifies, ensuring adhesion with the previous layer or the print bed. This fusion and extrusion process repeats until the complete fabrication of the object. FDM is widely used in 3D printing due to its simplicity, versatility and ability to produce functional parts with different properties. Due to the low strength of pure polymers, it is possible to reinforce them with fibers to enhance their mechanical properties [3].

Materials such as Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), and polyamide (PA) are widely used in FDM due to their low melting points, making them particularly suitable for 3D printing. As illustrated in Fig. 1, some polymers can be filled with particles or short fibers, where the addition of fibers increases the strength of the material. Moreover, it is possible to add continuous fibers to these polymers, providing an additional strength. Indeed, a composite material is up to 30 times stronger than plastic [4]. In addition to improve the mechanical properties, the incorporation of carbon fibers provides additional information about the material, such as its electrical and magnetic properties contributing to a more comprehensive understanding of intelligent materials [5]. 3D printing via FDM of this type of material is more complex, as it requires special attention during extrusion to ensure the continuity of the fiber arrangement within the polymer. The continuous fiber and thermoplastic are initially separated, and it is during printing that the two materials are melted together [6].

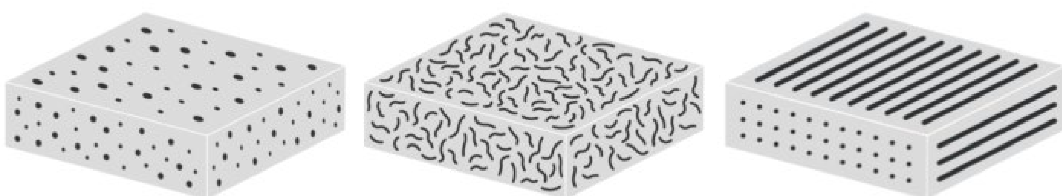

Figure 1: Composites reinforced with fibers (Image used with the permission of Anisoprint) [4].

Various technologies currently exist for extruding the composite material from a 3D printer nozzle in FDM. This paper compares dual-nozzle technology with coextrusion. Concerning dual-nozzle technology, Mark et al. [7] proposed a patented system using two nozzles, the first for depositing thermoplastic material and the second for laying down continuous fibers on the previously deposited polymer layer. Markforged is the brand that commercializes this patented technology. The reinforced polymer offered by Markforged is Onyx, which is composed of PA as the matrix material reinforced with short carbon fibers [8].

Coextrusion technology is a process characterized by the simultaneous extrusion of multiple materials, which may include polymers and reinforcing fibers, through a common nozzle. This method involves two distinct entrances: one for the polymer and another for the continuous fiber. Within the nozzle, the continuous fiber is integrated through the center of the polymer flow. The output from the nozzle yields a composite material tow [8]. Azarov et al. [9] explored the concept of pre-impregnating a fiber tow with a high-performance epoxy thermosetting polymer as a preliminary step. They proposed introducing these pre-impregnated fibers for in situ impregnation within a Fused Filament Fabrication (FFF) nozzle coated with thermoplastic. Adumitroaie et al. [10] explained that this method enables the utilization of the benefits associated with low-viscosity thermosetting polymers for impregnating the fiber tow, while also ensuring compatibility with the high viscosity of thermoplastic polymers in the FFF process. Anisoprint is the brand that developed this system. The reinforced polymer offered by Anisoprint is Smooth PA, which is composed of PA as the matrix material reinforced with short carbon fibers [4].

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In parallel with the developments in the design of these printers, the assessment of geometric capabilities and uncertainties of a printer is crucial. Therefore, to evaluate them, a Geometric Benchmark Test Artifacts (GBTA) is used to identify printing limitations. Moylan et al. [11] introduced a GBTA model with an extensive measurement range. Spitaels et al. [12] later enhanced Moylan's model by making it adaptive for many printers such as Pollen PAM Series MC, Ultimaker 2+, Ultimaker S3, offering a design covering more than 90% of the available printing area in the printer's X and Y axes [13].

The purpose of this study is to compare two 3D printers in terms of dimensional accuracy. The printers in question are the Mark Two by Markforged, using dual-nozzle technology, and the Composer A4 by Anisoprint, using coextrusion. To achieve this, three Geometric Benchmark Test Artifacts were printed by each printer and subsequently compared. The GBTA model of Spitaels et al. is used to analyze the Composer A4 (Anisoprint) and readjusted for the Mark Two (Markforged), considering its smaller print bed. Markforged uses Onyx as the material for printing GBTAs, while Anisoprint uses Smooth PA for the same purpose.

Procedure and Materials

The two printers have Cartesian architecture. The first one, Markforged's Mark Two printer, is built on dual-nozzle technology, as illustrated in Fig. 2(a). It enables the printing of thermoplastic with one nozzle and, on a separate head, the printing of continuous fiber using another nozzle. The print bed exhibits dimensions of 320 mm x 132 mm x 154 mm for its X, Y and Z axes. The second one, Anisoprint's Composer A4, stands out for its coextrusion method, as illustrated in Fig. 2(b). The fibers are pre-impregnated with a thermosetting epoxy polymer, creating a filament consisting of 1500 fibers. This filament is then directly impregnated into the nozzle by a thermoplastic material, thus forming the composite material that exits the nozzle. The printer offers a printing volume of 297 mm x 210 mm x 140 mm across its X, Y and Z axes.

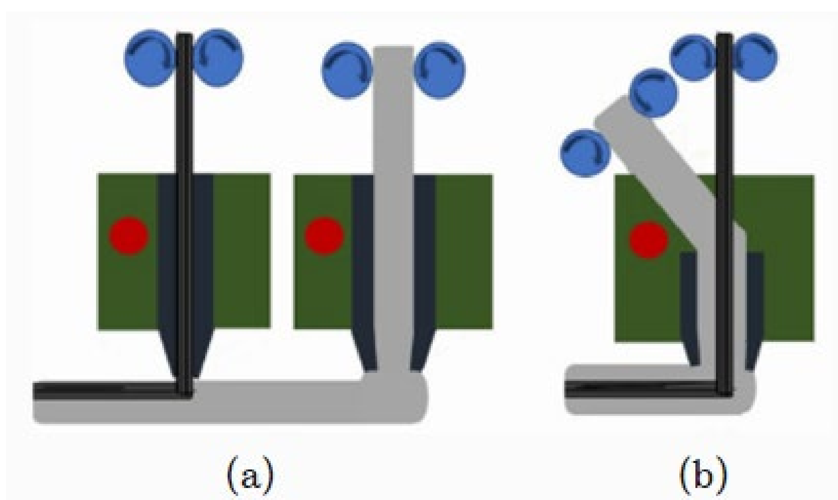

Figure 2 : Technologies of double buses (a) and coextrusion (b) [8].

These two printers serve as the primary tools for this study. Since their capabilities are not fully known, three GBTAs were printed for each printer to assess and compare their dimensional accuracy, providing insights into the anticipated tolerances of the resulting parts. The printing parameters are presented in Table 1. A 50% infill density was chosen to optimize printing time and save material. Despite this percentage reduction, the GBTA retains the necessary characteristics to fulfill its specific function as a measuring component.

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Table 1: Printing parameters of printers Mark Two (Markforged) and Composer A4 (Anisoprint)

	Mark Two (Markforged)	Composer A4 (Anisoprint)
Printing Time (h)	11h39	23h41
Infill Density [%]	50	50
Number of total layers	516	267
Layer thickness [mm]	0,050	0,100
FFF nozzle diameter [mm]	0,4	0,4
Build plate temperature [°C]	Not heated	60
Max nozzle temperature [°C]	275	270

Firstly, the size of the GBTA is selected to be compatible with the dimensions of each printer's build volume. As illustrated in Fig. 3, the GBTA size is smaller for the Mark Two printer than for the Composer A4, owing to the smaller dimensions of its print bed. Additionally, the GBTA is designed to facilitate the evaluation of the maximum surface of the build platform and enable the assessment of spatial repeatability. Indeed, the relative coverage of the build platform along the Y-axis is defined by Eq. 1.

$$Y_{GBTA}/Y_{Build\ plate} \tag{1}$$

Y_{GBTA} represents the length of the GBTA along the Y-axis, while $Y_{Build\ plate}$ corresponds to the length of the build plate of the printer. Eq. 2 is the practical application of Eq.1 by taking the Markforged printer as an example.

$$120.8/132\ = 91.5\% \tag{2}$$

The result obtained in Eq. 2 shows that the GBTA tests 91.5% of the Markforged printer's build plate along the Y-axis. It is worth noting that the chosen value of 120.8 mm, rather than the extreme possible dimension of 132 mm, is due to the necessity of incorporating a brim for enhanced adherence during the printing process. Evaluating the majority surface of the build platform is crucial as the precision of positioning devices can vary significantly between the center and corners [14]. However, it is important to highlight that the entire build plate has not been tested due to its rectangular shape, while the GBTA has a square shape.

Secondly, since the GBTA is intended to assess dimensional and geometric accuracy, it incorporates various features. These elements come in different sizes to cover the dimensional ranges specified in ISO286-1:1988 [15]. Indeed, to guarantee the proper functioning of a part, its dimensions must be between two limits defining the dimensional variation authorized in manufacturing, commonly called "tolerance". In the context of this study, all dimensions fall within the range of 1 to 174 mm and the IT range from 10 to 15. Simple geometric shapes such as cylinders, cubes, and planes are chosen to simplify the measurement process during analysis [16]. Dedicated orientation and position must be given to the features to relate the measured deviations directly to the cartesian axes of the machine and enable measurements using conventional measuring means, such as a Coordinate Measuring Machine (CMM) [11].

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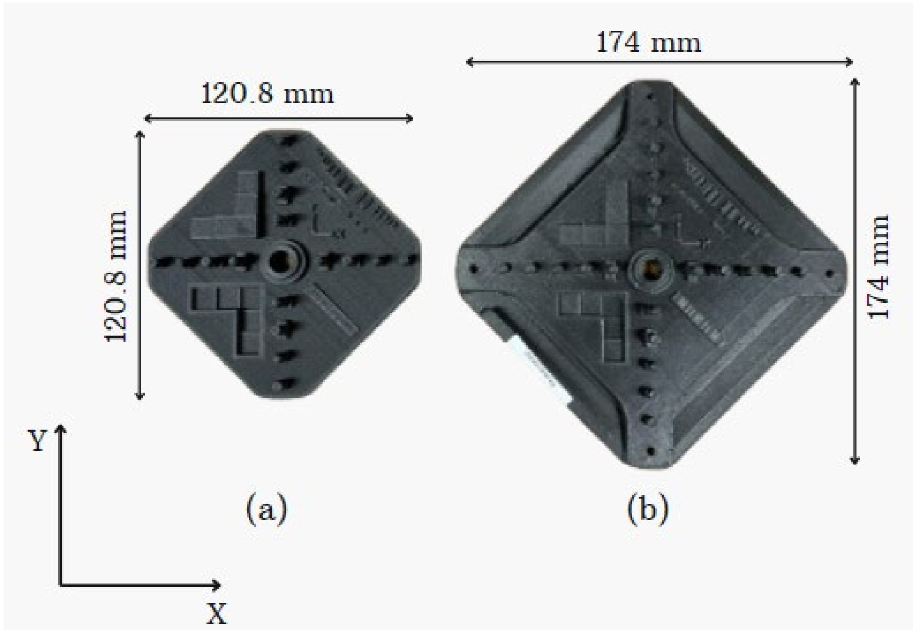

Figure 3: GBTA of Markforged (a) and GBTA of Anisoprint (b).

The CMM used to measure these GBTAs is a Wenzel LH 54. The measurement uncertainty of the machine for the X and Y axes is determined by Eq. 3 while for the Z axis, it is determined by Eq. 4.

$$3 + L/300 \tag{3}$$

$$3.5 + L/300 \tag{4}$$

The unit of uncertainty is micrometers, and the unit of the measured length L is in millimeters. The machine's resolution is 0.1 µm. There are 348 dimensional measurements for a single small GBTA, as depicted in Fig. 3(a), resulting in a total of 1044 measurements for the three GBTAs. Additionally, there are 395 dimensional measurements for the larger one in Fig. 3(b), totaling 1185 measurements. These measurements are grouped by zones on the GBTA. More specifically, there are measurements taken at the center of the GBTA, as illustrated in Fig. 4, measurements related to the three axes X, Y, and Z, and finally, the "other" measurement category which corresponds to the features relying on more than one axis, as a cylinder for example.

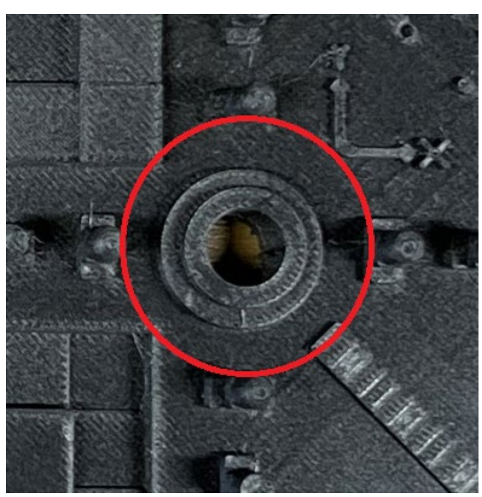

Figure 4: Center of GBTA

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Results and Interpretations

The results of the 3D printers from Markforged and Anisoprint discussed below address dimensional deviations of the studied features on the GBTA. The following two graphs, depicted in Fig. 5 and Fig. 6, focus on the tolerance intervals of the printers according to ISO 286–1 standards [15]. The maximum authorized values of the number of tolerance units for an IT is represented by the horizontal green bars. Therefore, if a measurement, with its error bars, is under a green horizontal bar, it means that it satisfies this IT. Each measurement has an associated error bar which indicates the repeatability of the printer. Indeed, the wider they are, the less repeatable the printer is. Regarding the y-axis of the graphs, it is important to note that they do not directly represent deviations but rather serve as an intermediate calculation. This is the reason why the y-axis is not explicitly represented. A detailed explanation of how this variable has been defined and measured is provided by Spitaels et al. [13]. For each of the graphs, the notation PA (polyamide) is used to refer to Smooth PA and Onyx and MKF represent the Markforged printer, while ANI is used for the Anisoprint printer.

The graph shown in Fig. 5 represents the tolerance intervals of ISO classes for dimensions ranging from 1 to 30 mm. In general, measurements are below the IT 14 standard. However, a notable exception concerns measurements between 6 and 10 mm at the center of the GBTA illustrated in Fig. 4 for Anisoprint, revealing significant deviations of up to IT 15. This issue does not appear to affect the Markforged. When visually inspecting the GBTA printed by Anisoprint and those printed by Markforged, it is noticeable that, within the central cylinder (Fig. 4), there are material residues and a surface condition that is not as clean as the GBTA printed by Markforged. This can be attributed to the fact that the layer thickness specified in Table 1 is twice as small for Markforged as compared to Anisoprint.

More specifically, when analyzing measurements between 1 and 10 mm at the center of the GBTA, significant deviations are observed (depicted by the blue bars) reaching IT15. On the other hand, for measurements from 10 mm and above, at the center of the GBTA, deviations are considerably lower, around IT 12. This suggests that, for all measurements related to the center of GBTA, both printers are more accurate in printing at the center of the print bed for objects with dimensions of 10 mm or more. Below this value, deviations are larger.

A cross-sectional observation of all measurements between 1 and 30 mm reveals that, for both printers, deviations along the X-axis (represented by the orange bars) are on average higher than deviations along the other two axes. This observation highlights a specific trend in deviations along the X-axis, indicating lower dimensional performances for features aligned with X-axis compared to the other axes. This observation can be attributed to the fact that, during printing, the printer nozzle, whether for Markforged or Anisoprint, covers a longer distance along the X-axis compared to the Y and Z axes. Indeed, the largest dimension of the build platform corresponds to the X-axis.

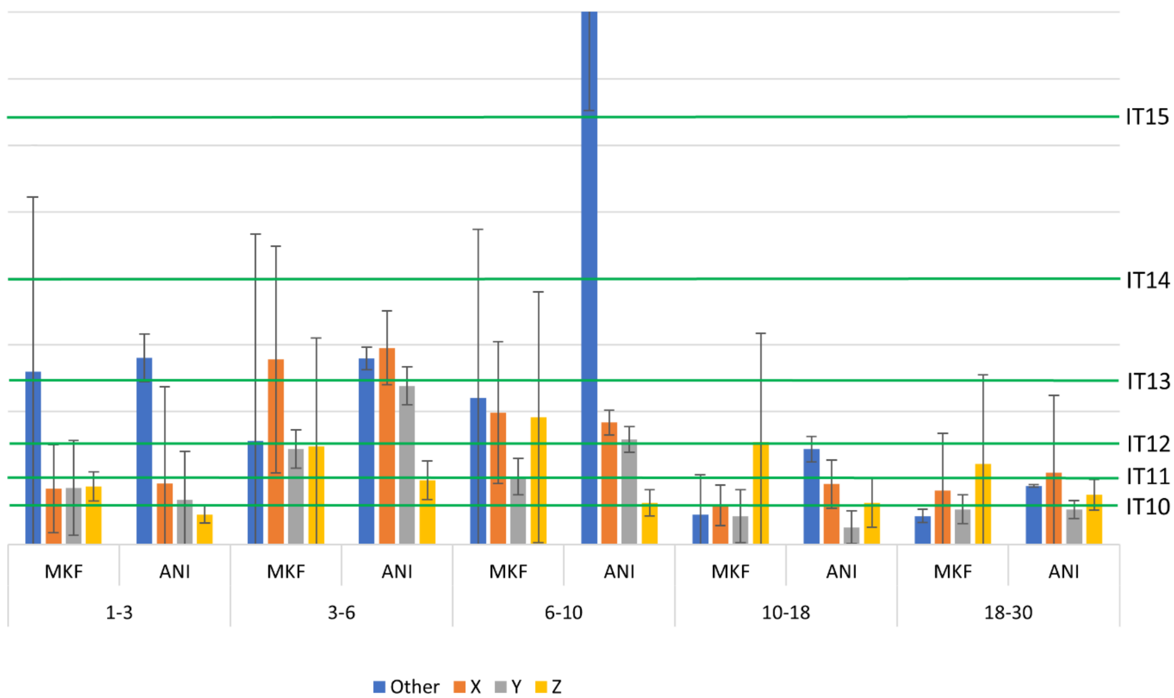

Figure 5: IT of printers Markforged (MKF) and Anisoprint (ANI) for ISO classes 1 to 30 mm

The diagram presented in Fig. 6 represents the tolerance intervals of ISO classes for dimensions ranging from 30 to 250 mm. It is noteworthy that there are no deviations for the Z-axis in this graph, as there are no measurements on GBTAs with dimensions exceeding 30 mm. Furthermore, there are no results for measurements between 180 and 250 for the Markforged, as the maximum dimension of its GBTA is limited to 120.8 mm.

Overall, it is observed that the deviations from the Anisoprint printer are generally smaller than those from Markforged. Globally, for both printers, the deviations do not exceed IT 13, except for deviations for measurements between 80 and 120 mm. A detailed analysis reveals that these deviations, illustrated by the blue bars in the graph in Fig. 6, correspond to distances between the planes representing the walls of the GBTA, as shown in Fig. 7.

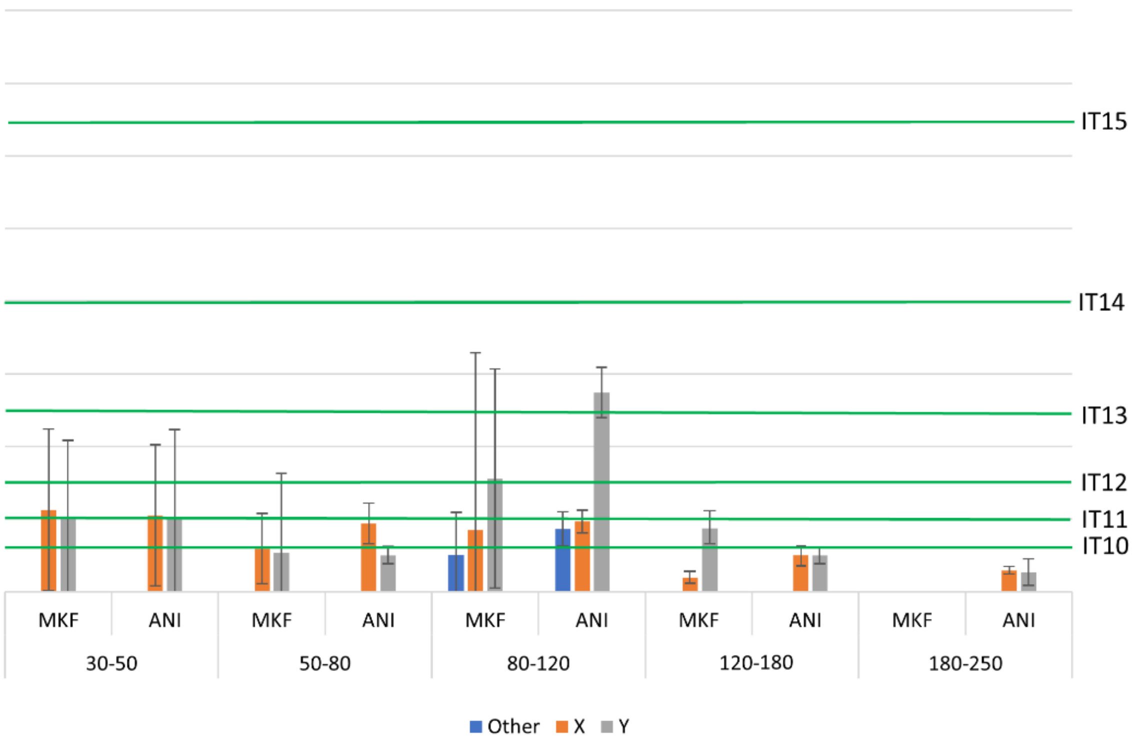

Figure 6: IT of printers Markforged (MKF) and Anisoprint (ANI) for ISO classes 30 to 250 mm

Figure 7: Walls of the Anisoprint's GBTA

The results indicate greater printing precision for Anisoprint, with deviations below IT 10, while for Markforged, the average is close to IT 12.

Regarding measurements between 30 and 80 mm, the highest deviations are observed in relation to the X-axis. However, when the measurements are higher, between 80 and 120 mm, the trend reverses. Deviations along the Y-axis then become more significant than those along the X-axis.

Furthermore, when examining both graphs (Fig. 5 and 6) on a global scale, we observe that deviations in measurements along the Y-axis are smaller for the Markforged printer than for the Anisoprint. This can be explained by the fact that the dimensions along the Y-axis of the Markforged print bed (132 mm) are smaller than those of the Anisoprint bed (210 mm). This implies that the print head of the Markforged has to travel a shorter distance than that of the Anisoprint. Besides, the deviations along the Z-axis are lower compared to deviations along the other axes. This suggests that both printers exhibit better precision regarding the vertical movement of their build plate compared to the movement of the print head. An essential consideration is the impact of the actuators utilized for movements in the X and Y directions, implemented through a belt-driven transmission with a guiding system. Concerning the Z-axis, a trapezoidal screw is employed to facilitate the movement of the print bed. Indeed, the amount of play in the movement of the print head and the build plate may vary depending on the specific printer.

Conclusions

In conclusion, this study systematically compared two Material Extrusion (MEX) technologies, specifically dual-nozzle and coextrusion, employed in 3D printers. The Markforged Mark Two, using dual-nozzle technology, was compared with the Anisoprint Composer A4, distinguished for its coextrusion method. Three Adaptive Geometrical Benchmark Test Artifacts (GBTA) were fabricated with each printer, and their dimensional performances were evaluated.

The results generally indicate that for both printers, dimensional performances are on average around IT 14. For measurements between 1 and 10 mm, the deviations are larger compared to those for dimensions greater than 10 mm, which on average are around IT 12.

Along the Y-axis, the Markforged exhibits smaller deviations in measurements that can be explained that it has a smaller print bed dimension along the Y-axis compared to Anisoprint.

Further analysis reveals that the Markforged printer demonstrates superior precision for smaller dimensions ranging from 1 to 30 mm, while the Anisoprint excels in precision for larger dimensions between 30 and 250 mm. Regarding precision along the Z-axis, both printers exhibit the same level of accuracy. Besides, the deviations along the Z-axis are lower compared to deviations along the other axes. This suggests that both printers exhibit better precision regarding the vertical movement of their build plate compared to the movement of the print head.

A notable observation highlighted significant deviations at the center of the GBTA concerning the other three axes (X, Y, and Z) for both printers. This comprehensive comparison sheds light on the dimensional and capabilities of dual-nozzle and coextrusion technologies, providing valuable insights for applications in continuous fiber reinforced thermoplastic composites (CFRTCs) and guiding future advancements in 3D printing technology.

Looking forward, exploring the incorporation of carbon fiber into the fabrication of the GBTA could lead to new research possibilities. Conducting a similar study with carbon fiber-reinforced prints would allow for an assessment of the impact of this advanced material on dimensional accuracy and overall performance. This perspective is particularly relevant as carbon fiber is known for its strength and lightweight properties, making it a promising candidate for enhancing the capabilities of 3D printing technologies.

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References

[1] ASTM D638, “Standard Test Method for Tensile Properties of Plastics 1”. https://doi.org/10.1520/D0638-14

[2] U. M. Dilberoglu, B. Gharehpapagh, U. Yaman, and M. Dolen, “The Role of Additive Manufacturing in the Era of Industry 4.0,” *Procedia Manuf*, vol. 11, pp. 545–554, 2017. https://doi.org/10.1016/j.promfg.2017.07.148

[3] F. N. Chaudhry, S. I. Butt, A. Mubashar, A. Bin Naveed, S. H. Imran, and Z. Faping, "Effect of carbon fibre on reinforcement of thermoplastics using FDM and RSM," *Journal of Thermoplastic Composite Materials*, vol. 35, no. 3, pp. 352–374, Mar. 2022. https://doi.org/10.1177/0892705719886891

[4] Read on https://anisoprint.com/ the 28 th October 2023.

[5] A. Demarbaix, I. Ochana, J. Levrie, I. Coutinho, S. S. Cunha, and M. Moonens, "Additively Manufactured Multifunctional Composite Parts with the Help of Coextrusion Continuous Carbon Fiber: Study of Feasibility to Print Self-Sensing without Doped Raw Material," *Journal of Composites Science*, vol. 7, no. 9, Sep. 2023. https://doi.org/10.3390/jcs7090355

[6] Maria Inês Santos Silva, "Non-Destructive Testing for Polymer Matrix Composites produced by Additive Manufacturing," Jul. 2020.

[7] G. T. Mark, R. B. Woodruff, A. L. Parangi, D. S. Benhaim, and B. Tsu Sklaroff, "Multiaxis fiber reinforcement for 3D printing," 2016.

[8] C. Pandelidi, S. Bateman, S. Piegert, R. Hoehner, I. Kelbassa, and M. Brandt, "The technology of continuous fibre-reinforced polymers: a review on extrusion additive manufacturing methods," *The International Journal of Advanced Manufacturing Technology*, 2021. https://doi.org/10.1007/s00170-021-06837-6

[9] A. V. Azarov *et al.*, "Development of a two-matrix composite material fabricated by 3D printing," *Polymer Science - Series D*, vol. 10, no. 1, pp. 87–90, Jan. 2017. https://doi.org/10.1134/S1995421217010026

[10] A. Adumitroaie, F. Antonov, A. Khaziev, A. Azarov, M. Golubev, and V. V. Vasiliev, "Novel continuous fiber bi-matrix composite 3-D printing technology," *Materials*, vol. 12, no. 18, Sep. 2019. https://doi.org/10.3390/ma12183011.

[11] S. Moylan, J. Slotwinski, A. Cooke, K. Jurrens, and M. A. Donmez, "An additive manufacturing test artifact," *J Res Natl Inst Stand Technol*, vol. 119, pp. 429–459, 2014. https://doi.org/10.6028/jres.119.017

[12] L. Spitaels, E. Rivière-Lorphèvre, A. Demarbaix, V. Thielens, and F. Ducobu, "Dimensional and geometrical performance assessment of two FDM printers using a benchmark artifact," 2021.

[13] L. Spitaels, E. Rivière-Lorphèvre, A. Demarbaix, and F. Ducobu, "Adaptive benchmarking design for additive manufacturing processes," *Meas Sci Technol*, vol. 33, no. 6, Jun. 2022. https://doi.org/10.1088/1361-6501/ac5877

[14] L. Rebaioli and I. Fassi, "A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes," *International Journal of Advanced Manufacturing Technology*, vol. 93, no. 5–8, pp. 2571–2598, Nov. 2017. https://doi.org/10.1007/s00170-017-0570-0

[15] International Organization for Standardization 1988 ISO 286–1.

[16] M. A. de Pastre, S. C. Toguem Tagne, and N. Anwer, "Test artefacts for additive manufacturing: A design methodology review," *CIRP Journal of Manufacturing Science and Technology*, vol. 31. Elsevier Ltd, pp. 14–24, Nov. 01, 2020. doi: 10.1016/j.cirpj.2020.09.008