The dimensional accuracy of plastic parts made by the fused filament fabrication

M A Boca¹, A Sover ² and L Slătineanu¹

¹Machines Manufacturing Technology Department, “Gheorghe Asachi” Technical University of Iași, Romania
² Technology Departments, University of Applied Sciences, Ansbach, Germany

E-mail: boca_marius94@yahoo.com

Abstract. Fused filament fabrication (FFF) process has gained considerable public interest in the last years and due to its numerous advantages, a study that identifies and explains the influence of used plastic materials on the accuracy of the parts achieved by FFF could be considered as necessary. The present study contains a brief introduction in the additive manufacturing basic notions, technologies, and equipments. In a similarly manner the 3D scanning process is also synthetically presented. The main focus is on studying the accuracy of test parts obtained in laboratory conditions using the most used 5 polymer materials (PLA, ABS, PP, PA and PET). The experiments were conducted using software and equipment dedicated to 3D printing for FFF-technology and optical scanning. Results sustained by graphs, tables and images showed that the ABS type material provided the best results concerning the linear dimensional accuracy along the X and Y axes. For the circular and linear dimensions accuracy along the Z-axis, the lowest deviations in comparison with the nominal dimensions were found in the case of the test part made of PLA. The experiments also proved that the materials that had a higher proportion of the studied points included in the tolerance zone were the PLA and the PET.

1. Introduction
Due to the extended use of the plastic materials in domains like construction, automotive, agriculture, electronics and electro-technics, medicine, food industries and many others fields, the manufacturing processing like injection moulding and extrusions are highly applied. Due to the many advantages, new manufacturing processes gained a considerable industrial and public interest and one of such processes was the 3D printing. This manufacturing process is also known under other names, such as additive manufacturing (AM), fast/rapid manufacturing (RM), or even rapid prototyping (RP). Although the 3D printing concept is widely spread and independently used, it could be considered as a subset of the additive manufacturing processes.

The particular aspect of the additive manufacturing processes is that the desired part is generated by adding layers upon layers of material, unlike the common traditional manufacturing, where the part is generated by removing the excess material form the work piece (using the milling, turning, drilling, carving, shaping, etc. or considering initial a casting or forging process followed by a subtractive manufacturing process). Based on the standards ISO/ASTM 52900:2015 – Additive manufacturing - General principles – Terminology and ASTM F2792-12A:2015 - Standard Terminology for Additive Manufacturing Technologies”, there are many groups of 3D printing processes that can be classified

into seven categories: material extrusion, vat photo-polymerization, binder jetting, material jetting, powder bed fusion, directed energy deposition and sheet lamination [1, 2].

One of the most commonly available and cheapest additive manufacturing technologies, due especially to the presence of the hobby type equipment (desktop 3d printer) and industrial applications, is the fused filament fabrication (FFF), as a component of the material extrusion group. The process uses, for example, a spool of plastic or composite materials filament, that can have 1.75 mm or 2.85 mm in diameter, loaded into the 3D extrusion head and fed through a heated printer nozzle (that have a hole with a diameter in the range from 0.1 mm to 1.2 mm). Stepper motors are used to move the extrusion head and the heated bed along with specified coordinates defined in the .gcode file, which is read by the 3D printer. The melted material is seated layer-upon-layer and cold down and solidifies on the build plate, forming the desired part.

A wide range of thermoplastic polymers, like standard plastic, engineering plastics, composite material with polymeric matrix and short or long hard fiber, high performance or ceramic, hard metals, non-ferrous metals, and stainless steel can be used.

In the last years, the researchers were interested in studying the influence exerted by the input factors of the 3D printing process on the accuracy of the manufactured parts. Thus, Greef and Schilling investigated the possibilities of optimizing the fused filament fabrication process to improve the dimensional accuracy of the manufactured part [3]. They used the least squares regression to establish linear models for the stringing length.

Moza et al. used a Taguchi L9 orthogonal design to investigate the effect of printing material, infill rate, number of shells, and layer height on the linear dimensions of the printed part [4]. They achieved an analysis of variance to identify the importance of each process input parameter.

The results which are presented in this paper, besides the printing process, a major used technology was the 3D scanning, which is a technique that uses an optical 3D scanner to analyse a real-world object, person or environment, to collect data on its shape and possibly to capture images concerning its aspect. In this way, information concerning the object 3D shape can be saved, edited, and afterward, 3D printed.

The non-contact 3D scanners are powerful tools used in several industries, such as automotive, aeronautics, for robotic mapping, industrial design, reverse engineering and prototyping, and non-destructing quality control/inspection, in archaeology by digitization of the cultural artefacts, jewellery, and other relics, in medicine (in the computed tomography or for orthotics and prosthetics), and stomatology, as well as motion capture and gesture recognition for video games, augmented reality, special effects, and animation movie [5]. Other aspects were also taken into consideration when the researchers investigated the accuracy of the plastic part manufactured using the fused filament fabrication process [6-11].

Based on the extended applications of the plastic materials and due to the fact, that in the last years, the FFF process has gained considerable public interest, a study aiming to identify and explain some of the problems and advantages of this process could be considered as necessary. The objective was to measure different dimensions on 5 3D-FFF printed parts made from the most used 5 polymer based materials (Polylactic Acid - PLA, acrylonitrile butadiene styrene - ABS, polypropylene - PP, polyamide - PA and polyethylene terephthalate - PET) and the accuracy of the resulted test. Another objective was to seek and characterize the dimensional accuracy of the test parts using software and equipment dedicated to 3D scanning. The accuracy of the parts could be considered as essential to ensure better functionality of the parts, but at the same time, it can influence the production or post-processing time and implicitly the costs of the parts.

2. Methodology

All tests have been conducted in laboratory conditions, and the research has been divided into two major stages: first stage that aimed to establish the printing parameters and to print the test part for each material separately and the second stage that aims to study of surface quality and dimensional accuracy using software and equipment dedicated to the 3D scanning process. The printing parameters
were established taking into account the recommendations of the equipment manufacturer, technical sheet from the material producers and the information found in various other works. Also a series of testing can be made in order to identify the right parameters.

In order to decrease the necessary time for finding the right process parameter a series of testing have been made. A Temperature Test Tower, design by Mike Cameron (figure 1 a.) it is mandatory alongside with a stringing test and a "All in One 3D Printed Test", design be Marián Trpkoš. The “All in One 3D Printed Test” (figure 1 b.) is a part that contain test for tolerance accuracy, bridging, overhang, stringing, sharp corners and diameters.

(a) Temperature Tower Test              (b) *MICRO* All In One 3D printer test

Figure 1. 3D printing tests. [12, 13]

Physical or chemical post-processing treatment or other modification or that may lead to the modification of overall shape and surface of the printed test parts was forbidden and not used. Scanning of the parts made of different materials was a cyclic process that started with the preparation of the parts, the scanning, and the study of the different points positions and dimensional accuracy for each test part.

To obtain conclusive information concerning printing accuracy, for all test parts, at least 16 similarly positioned points and 4 random points for every test part and compared the final result to the CAD version and to each other. As can be seen in figure 2, the chosen points were the following: 5 points on the bottom surface, at least 3 points for each lateral side and on the top surface and at least one point for each frontal side.

Figure 2. Establishment of the placement of the points on the test part surfaces.

To study the dimensional accuracy, we considered 5 dimensions highlighted in figure 3 and compared these values obtained from the GOM Inspect software with the initial CAD dimensions. The selected dimensions were the following: A= 100 ±0.1 mm (along the X-axis), B= 20 ±0.02 mm (along the Y-axis), C= 12 mm (diameter), D=10 mm (along the Z-axis) and E= 3 mm (radius).
2.1. Equipment, material, and software
To achieve the test parts, an Ultimaker 2+ 3D printer was used. This equipment is a reliable and robust Cartesian, single Bowden extrusion 3D printer, with a 0.4 mm brass nozzle size and that works with filaments of 2.85 mm in diameter. Other important features are a nozzle temperature that can go up to 260 °C, in less than 2 minutes and a glass build plate that can reach a temperature of 115 °C with assisted levelling. Besides that, a front enclosure that ensures a protected medium from external air currents, keeps the warmth from the heated bed inside the printer, consequently creating a stable environment with a constant temperature of 45 ºC. The enclosure is very effective when printing with materials that have a higher printing temperature and are prone to warp and layer bonding problems (delaminating).

The materials used to achieve the test parts were the following: 2.85 mm red, blue and white PLA, red and white ABS, white ERP InnoPET (from the Innofil3D Company), natural PP from the Ultimaker Company and clear colour PA, from the Form Futura Company. The print time resulted, for creating the final scanned samples, from figure 4, are: 3.56 h for the PLA sample, 4.33 h for the ABS sample, 4.43 h for the PP sample, 3.47 h for the PET sample and 3.10 h for the PA sample.

![Figure 3. Dimensions considered in experimental research.](image)

![Figure 4. 3D printing tests.](image)
Equipment used to scan and study the test parts was an ATOS Core 200 from GOM Company, which is a manually operated system and 2 software, GOM Inspect and GOM Scanning 2017. The projection unit of the ATOS Core system is based on Blue Light Technology, which is a non-contact optical with a triple scan technology that measures millions of accurate points per quick scan. After scanning each test part, using the GOM Scan software, the quality of the surface and the dimensional accuracy has studied and compared with the CAD file using the GOM Inspect software.

2.2. Experimental study and results
Each scanning process started with sticking of the markers, at least one marker for each face, but the effective numbers of markers depend on the complexity of the test part. After the markers were applied to each face of the test part, an anti-reflection coating spray was used to cover the test part. The cleaning of the markers of the spray layer was followed by clamping the test part on the rotational platform. Afterward, the scanning process started by investigating the upper zone of the test part, cutting the unwanted surfaces (rotational platform, fastening devices, etc.), and by rotating the test part, with the bottom surface on top, and repeating the above-mentioned steps.

After just one scan (figure 5 a.), the piece starts to be defined by the software. Both part images (figure 5 b.) obtained are joined together to generate the final image of the scanned test part, by selecting and matching at least 3 points from the same surface. The result was exported in a .stl file to be further analysed or to be printed again.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Top and bottom scanned surfaces.

Changing the software to GOM Inspect, the analysing process can start. Usually, at this stage, the part is verified to do not have any errors (holes in the surface, additional parts from the previous steps, etc.). After fulfilling this stage, the surface analysis can be developed by overlapping and aligning the CAD version (.stp file) of the test part.

It can be noticed that for the PLA test part, the investigated points, from figure 6 a. have values of the deviations from -0.18 mm up to +0.07 mm. The shrinkage of the ABS and PP test parts is more pronounced in the edges or corner areas, based on the negative values, from -0.55 mm for the ABS test part and -0.64 for PP test parts. The PP test part shows no signs of warping or other problems specific to the PP printed test part. This is not the case when the surfaces are analysed using the GOM Inspect software, instead of a simple visual inspection. The shrinkage of the PA test part from figure 6 b is more pronounced on the edges and corners, based on the blue colour and the negative values, from -0.60 mm up to -1.26 mm for the points found in the edges or corner areas. Similar to the PLA test part, the PET test part presents no major problems, except for a few negative values (-0.57 mm, -0.34 mm
and -0.25 mm) in 2 different corners. Studied values and wall shape indicate a good selection of the printing parameters.

![PLA test part](image1)

(a) PLA test part

![PA test part](image2)

(b) PA test part

Figure 6. Value of the considered points found on the test parts.

The 5 dimensions to be compared, the tolerances, and the value of the deviation from the nominal dimension for test parts made from PP and PA are presented in figure 7. The shrinkage of the PP test part is not observed just on the edges and corners areas, but it affects the front, the top, and the lateral surfaces, too. The most affected dimension is the dimension A (100 ±0.1 mm), which is affected by a decrease of 0.58 mm. Even the fact that the edges, corners, and bottom surface show signs of warping for the PA test part, the dimensions investigations showed no sign of major deformation. The dimensions are quite accurate and can also be compared with the PLA dimensions, with the exceptions of the dimension D=10 mm (along the Z-axis), which was characterized by an increase of 0.66 mm.

![PP test part](image3)

(a) PP test part

![PA test part](image4)

(b) PA test part

Figure 7. Values of the deviations found on the PP and PA test parts.

The section view achieved alongside the Y-axis and presented in figure 8 offers a better highlighting of the difference between the actual form of the wall-A and the CAD wall shape-B. The difference between the overall shape of the walls and the ideal wall shape from the CAD file is more pronounced in the case of the ABS test part, due to the shrinkage effect. Similar behaviours have been obtained in the cases of the PA and PP test parts.
The numerical values of the studied points presented in table 1 indicate the distance, in mm, from the real profile to the CAD profile, for each individual selected point.

**Table 1. Values of the study points.**

| Point no. | Deviation value for PLA [mm] | Deviation value for ABS [mm] | Deviation value for PP [mm] | Deviation value for PA [mm] | Deviation value for PET [mm] |
|-----------|------------------------------|------------------------------|----------------------------|-----------------------------|----------------------------|
| 1         | -0.14                         | -0.04                        | -0.22                      | -0.34                       | -0.60                      |
| 2         | -0.18                         | -0.08                        | -0.10                      | -0.17                       | -1.26                      |
| 3         | -0.08                         | -0.16                        | -0.06                      | -0.10                       | -0.86                      |
| 4         | -0.06                         | -0.21                        | -0.11                      | -0.34                       | -0.74                      |
| 5         | -0.04                         | -0.50                        | -0.40                      | -0.19                       | -0.13                      |
| 6         | -0.12                         | -0.02                        | -0.07                      | -0.22                       | -0.12                      |
| 7         | 0.03                          | -0.45                        | -0.35                      | -0.16                       | -0.06                      |
| 8         | 0.00                          | -0.02                        | -0.12                      | -0.02                       | -0.10                      |
| 9         | 0.05                          | -0.16                        | -0.06                      | -0.60                       | -0.28                      |
| 10        | 0.01                          | -0.38                        | -0.28                      | -0.23                       | -0.13                      |
| 11        | 0.03                          | -0.55                        | -0.45                      | -0.51                       | -0.24                      |
| 12        | 0.05                          | -0.06                        | -0.24                      | -0.41                       | -0.14                      |
| 13        | 0.07                          | -0.51                        | -0.41                      | -0.11                       | -0.01                      |
| 14        | 0.04                          | -0.44                        | -0.34                      | -0.64                       | -0.54                      |
| 15        | 0.02                          | -0.05                        | -0.46                      | -0.36                       | -0.12                      |
| 16        | 0.02                          | -0.54                        | -0.44                      | -0.33                       | -0.24                      |
| 17        | 0.04                          | 0.00                         | -0.04                      | -0.08                       | -0.08                      |
| 18        | 0.02                          | 0.08                         | 0.00                       | -0.07                       | -0.07                      |
| 19        | 0.34                          | 0.24                         | 0.06                       | 0.04                        | -0.07                      |
| 20        | 0.16                          | 0.06                         | -0.22                      | 0.04                        | -0.02                      |

**Figure 8.** Section view of the ABS part.
2.3. Study summary
As can be seen in table 1, the chosen points for PLA test part are included in a tolerance range of ±0.1 mm in a proportion of 75 % and the average of the deviation is 0.013 mm, while the average of those 5 points with values that exceed the tolerance zone is 0.032 mm. For the ABS test part, the points are included in the tolerance range of ±0.1 mm in a proportion of 40 %, and the average of the deviation is -0.212 mm, while the average of the 12 points with values that exceed the tolerance zone is -0.25 mm. The chosen points for the PP test part are included in a tolerance range of ±0.1 mm in a proportion of 25 %, and the average of the deviation is -0.236 mm, while the average of the 15 points with values that exceed the tolerance zone is -0.25 mm. For the PA test part, the points are included in a tolerance range of ±0.1 mm in a proportion of 35 %, and the average of the deviation is -0.295 mm, while the average of the 15 points with values that exceed the tolerance zone is -0.31 mm. For the PET test part, a proportion of 60 % of points included in the tolerance range of ±0.1 mm has been obtained, and the average of the deviation is -0.045 mm, while the average of the 8 points with values that exceed the tolerance zone is -0.106 mm.

Using the information from table 1 for each material, the graph from figure 9 was achieved, and as can be seen, the graphic representations of PLA specific points are the closest one and best fits into the tolerance field, followed by the PET material-specific points.

![Figure 9. Deviation values of the investigated points.](image)

From the figure 10, it can be observed that the materials with a proportion of the points included in the tolerance zone higher than the proportion of the points that are out from the tolerance zone are PLA and PET.

![Figure 10. Percentage of the points included in the tolerance.](image)

The values of the dimensions obtained from 3D scanning are compared with the dimensions chosen from figure 3. For dimension A, it can be seen from figure 11 that only in the case of test parts printed
of ABS and PA the considered dimension founds within the tolerance field. The largest deviation from the imposed size corresponds to the PP test part, where the difference is 0.58 mm. Only in the case of the E-ray, all the 5 test parts are characterized by a deviation that founds within the tolerance field, as can be seen in figure 11, and the lowest value of the deviation is 0.03 mm for test parts from PLA and ABS.

Figure 11. Dimensional accuracy for the dimension $A = 100 \pm 0.1 \text{ [mm]}$ and radius $E = 3 \pm 0.1 \text{ [mm]}$.

Following the 3D printing of test part and scanning results of the B, C, and D quotas, figure 12, it can be seen that none of the odds founds within the tolerance field. In all the cases, the highest deviation from CAD dimensions was found in the case of the test part made of PET.

Figure 12. Dimensional accuracy for the dimensions $B = 20 \pm 0.02 \text{ [mm]}$, $C = 12 \pm 0.1 \text{ [mm]}$ and $D = 10 \pm 0.1 \text{ [mm]}$.

Table 2 includes a conclusion of the results of measurements do to comparing the materials using criteria applied to identify the advantages and disadvantages of each material and to facilitate the selection of materials in different situations.

Table 2. Conclusion and material corporation for the 5 used polymers.

| Comparison criteria                        | Best results | Alternative option |
|--------------------------------------------|--------------|--------------------|
| Print time                                 | PA           | PLA/PET            |
| Print speed                                | PLA          | PA                 |
| Problems during printing                   | PLA          | PET                |
| Average of the deviation values            | PLA          | PET                |
| Percentage of the deviation bigger than 0.1 mm | PLA          | PET                |
| Linear dimension along X-axis             | ABS          | PA                 |
| Linear dimension along Y-axis             | ABS          | PA                 |
| Linear dimension along Z-axis             | PLA          | PP                 |
| Circular dimension (Diameter, Radius)      | PLA          | ABS                |
3. Conclusion

Using 3D printing, different useful plastic objects can be produced. In the present paper, the results of an experimental investigation concerning the accuracy parameters obtained in the case of using 5 polymer-based materials (PLA, ABS, PP, PA, and PET) and the FFF technology were presented. The tests aimed to identify the dimensional accuracy of different test parts, using software and equipment dedicated to 3D scanning and printing. When applying 3D printing, the deviations from the CAD profile are inevitable, and this could be the reason for which material like PLA is often recommended, due to the possible low average deviation values in comparison with the desired values. It is important that the percentage of occurrence of deviations values less than 0.1 mm be as close as possible to 100%. As a consequence of the experimental research, it can be noticed that the materials that have a proportion of the dimensions included in the tolerance zone (0.1 mm) higher than the proportion of the dimensions placed out of the tolerance zone are PLA and PET.

If the linear dimensional accuracy is analysed, the best result was offered by the ABS material, followed by the PA material for the dimension measurement along X, respectively Y-axis. In what concerns the circular dimension and linear dimension accuracy, along the Z-axis, no material could provide a deviation that is within the tolerance field, but the smallest deviation that exceeds the tolerance field was found in the case of the test part made of PLA.

Further studies could take into consideration the complexity of the subject and the possibilities offered by combining the FFF printing with 3D scanning process.

References

[1] ISO/ASTM 52900:2015- Additive manufacturing - General principles – Terminology
[2] ASTM F2792-12A:2015- Standard Terminology for Additive Manufacturing Technologies
[3] Greeff, G P, Schilling M 2018 Single print optimisation of fused filament fabrication parameters International Journal of Advanced Manufacturing Technology 99, 845–858
[4] Moza Z, Kitsakis K, Kechagias J, Mastorakis N 2015 Optimizing dimensional accuracy of fused filament fabrication using Taguchi design Proceedings of the 14th international conference on instrumentation, measurement, circuits and systems (IMCAS '15), 110–114
[5] 3D scanning technologies and the 3D scanning process 2019 Aniwaa available: https://www.aniwaa.com/3d-scanning-technologies-and-the-3d-scanning-process/ accessed: 14.07.2019
[6] Sahu K M, Mahapatra A 2013 Study on dimensional accuracy of fused deposition modeling (FDM) processed parts using fuzzy logic Journal for Manufacturing Science and Production 13(3), 183-197
[7] Redwood B 2016 Dimensional accuracy of 3D printed part. Available: https://www.3dhubs.com/knowledge-base/dimensional-accuracy-3d-printed-parts/ Accessed: 14.05 2020
[8] Bahr F, Westkamper E 2018 Correlations between influencing parameters and quality properties of components produced by fused deposition modeling Procedea CIRP 72, 1214-1219
[9] Sudin M N, Shamsudin S A, Abdullah M A 2016 Effect of part features on dimensional accuracy of FDM model ARPN Journal of Engineering and Applied Science 11, 8067–8072
[10] Simsek S, Yaman U 2016 Dimensional accuracy improvement of fused filament fabrication holes utilizing modified interior 19th International Conference on Electrical Machines and Systems (ICEMS) pp 1-6
[11] Alizadeh M, Esfahani M N, Tian W, Ma J 2020 Data-driven energy efficiency and part geometric accuracy modelling and optimization of green fused filament fabrication processes Journal of Mechanical. Design 142(4), 041701
[12] Cameron M 2018 Temperature Tower With Shapes. Availed at: https://www.thingiverse.com/thing:2761934 access: 07.05.2018;
[13] Trpkoš M 2018 *MICRO* All In One 3D printer test. Available at: https://www.thingiverse.com/thing:2975429 access: 07.05.2018;