ACCURACY ANALYSIS OF ADDITIVE TECHNIQUE FOR PARTS MANUFACTURING

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The article introduces accuracy analysis results of additive technique used for manufacturing of parts depending on the used Rapid Prototyping technology. The main goal of the research was to complexly analyse dimensional and shape accuracy of parts manufactured by means of the selected 3D printers, and to compare the obtained results with the parameters given by the printer manufacturers. Devices such as Stratasys Dimension SST 768 printer using the FDM principle and Objet Connex 500 using the *PolyJet Matrix* were used for the verification purposes. The measurement of the selected models was performed using modern optical digitisation methods, specifically by means of 3D contact-less scanners. The subsequent data evaluation and verification of the actual part compared to the nominal CAD model was performed using GOM Inspect Professional.

KEYWORDS

additive technology, 3D Print, fused deposition modelling, polyJet matrix, geometrical accuracy, 3D optical scanner, 3D digitization.

1 INTRODUCTION

Additive technologies are currently an indispensable part of many branches of industry. Their benefits are widely used fields such as engineering, construction or medicine. The Rapid Prototyping technology, a manufacturing method using 3D printing, contributes on shortening the development time and innovation of new products in a significant manner. The grand advantage lies in the possibility to manufacture parts and shape that are otherwise not manufacturable using other technologies. Contrary to conventional machining, where the material is being removed, the Rapid Prototyping technologies use exactly opposite approach – adding material in layers.

In recent years, the Rapid Prototyping technologies using plastic materials of various compositions for prototype manufacturing were hugely expanded. Among the best known and most widely used are for example ***Selective Laser Sintering*** (SLS) technology that utilises a high-power laser beam to melt and sinter fine grains of the print material to form a required shape, or a method similar in principle – ***Stereolitography*** (SLA) that draws the individual layers of an object by means of ultra-violet laser beam on a surface of a polymer liquid.

Other widely spread technologies are ***Fused Deposition Modelling*** (FDM), ***Multi Jet Modelling*** (MJM), or ***PolyJet Matrix***.

However, each of the manufacturing technologies has its limits regarding the ability to create small details or manufacture the parts with the required accuracy. In order to be able to choose the right technology for the required part or predict an eventual inaccuracy of the manufactured part caused by the specific printer, it is good to be familiar with the limits of each of the manufacturing devices. Despite the fact that most manufacturers provide with the data regarding accuracy of their 3D printers, our experience shows that in non-laboratory conditions, these accuracy values are hard to reach.

There is quite a lot of publications regarding the Rapid Prototyping technology, however, these often focus on the ways of using the additive technologies for manufacturing of various specific parts (prototypes, lightweight constructions, healthcare products) and address the research of products' mechanical properties, or evaluate and compare the 3D printing methods of manufacturing with the conventional ones. Nevertheless, there are not many papers addressing the accuracy evaluation of 3D printers. If there were such articles, they focused on research of geometrical accuracy of the 3D printing, other printer types, or did not address the issue sufficiently and complexly.

For example, a team of authors [Melenka 2015] performed an experiment in order to determine material properties and dimensional accuracy of MakerBot Replicator 2 desktop 3D printer. This printer would more likely be categorised to "hobby printers", therefore it is not surprising that the analysis of dimension led determination that the values significantly differed from the prescribed nominal dimensions. One of the few works addressing technologies similar to those in our research is [Lee 2015]. Models in this research were manufactured by means of FDM and Polyjet, however, the study was focused on accuracy of teeth replicas rather than shapes and products used in engineering. The results of the research led o conclusion that most models manufactured by means of the FDM method tended to be slightly smaller, whereas the models made using the PolyJet technology were slightly larger. An average deviation with BestFit alignment was - 0.047 mm with FDM and + 0.038 mm with PolyJet. Another interesting publication regarding a similar topic is [Álvarez 2014]. The research described in this literature focuses on analysis of sampling strategy impact on the dimension and geometrical properties of the parts manufactures by means of the PolyJet technology. One of the older researches, [Sood 2009], focused on the FDM technology. The authors performed experiments to determine the influence of important process parameters (such as layer thickness, part orientation, screen angle, internal structure) on dimensional accuracy of the FDM technology. They found out that the shrinkage occurs mainly along the length and width of the printed model. Conversely, in the thickness direction, a positive deviation from the required value was observed. Additionally, the research described in this publication focused on finding suitable printing parameters in order to eliminate errors and came to a conclusion that the optimization process of printing parameters is very complex and no theoretical model for prediction of errors can be determined.

During researches, several additional studies focusing on manufacturing accuracy using SLM method and metallic materials were found. The accuracy of manufacturing and testing with various parameter settings for construction using SLM technology is for example described in [Ilčík 2014]. The tests described in this publication were focused on determining the influence of individual parameters of part manufacturing on surface quality and outer dimensions. The [Królikowski 2013] also addressed the inspection of dimensions using the SLM method. In this case, it is a dimensional inspection of part with thin walls.

As the performed research implies, other projects regarding a similar topic often solve only partial analysis or unilaterally oriented experiments. And in case there are projects dealing with for example dimensional properties of samples, the overall shape stability is not regarded at all. Therefore, we focused on own research, where we performed a complex analysis of abilities of the selected printers to maintain the prescribed dimensional and shape production quality.

2 USED 3D PRINTING TECHNOLOGIES

The ***Fused Deposition Modelling*** (FDM) is one of the most widespread methods of 3D printing, not just on the professional level. FDM is an additive technology developed in the late 80s by S. Scott Crump, who also patented it in 1989 and later founded a company – Stratasys. Most commonly, the principle of the FDM lies in melting a thermoplastic material in a form of a thread inside an extrusion head that extrudes the melt onto a pad. Due to its 2-axis movement, it gradually applies a thin layer of material in the product's horizontal cross-section plane. Layer thickness usually ranges from 127 to 254 micrometres. The material is heated in the nozzle to a temperature of 1 °C above its melting point. After the application of a whole layer, the pad is vertically lowered by the layer thickness, followed by applying another layer, while this process repeats until the whole product is manufactured. Additionally, a supporting structure is created when the protruding parts requires it, while after the model is finished, the supports are removed in a mechanical or chemical way. The most common materials for FDM are ABS and PLA thermoplastics. Also, polyamide, polyethylene, or wax can be used for the manufacturing process.

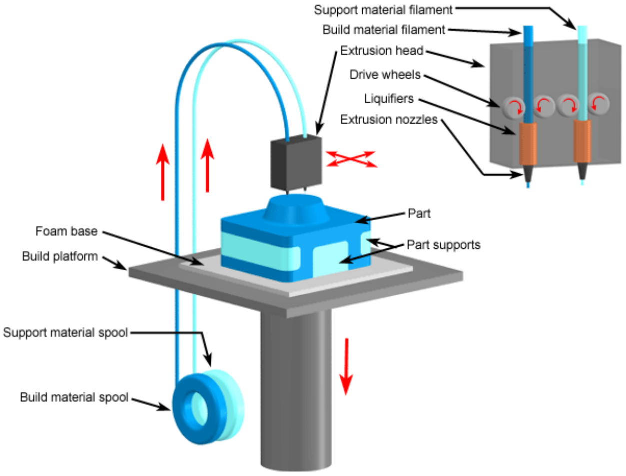


Figure 1. The principle of FDM method [Custompart.net 2016]

The principle of ***Multi Jet Modelling*** (MJM) lies in gradual application of individual layers of polymer on top of each other using a special printing head. The head is fitted with multiple nozzles arranged to be parallel to one another. The flow of the applied material of controlled individually for each nozzle. Same as in the previous case, the model is being manufactured on a support pad that is being moved in X-axis by a working head. In case the part is wider than the working head itself, it can additionally be moved in Y-axis. The high number of nozzles guarantees quick and even material application.

Essentially, ***PolyJet Matrix*** is the MJM technology. The difference between these two technologies is the used material – photo-polymer, which is then subsequently hardened by means of UV lamp. The *PolyJet Matrix* is the first RP technology that allows application of two types of resins during a single manufacturing process. Due to the simultaneous dosage and mixing of two-component mixtures, it is possible to print physical models with various mechanical and physical properties in a single manufacturing process. In addition, the method offers high accuracy of details.

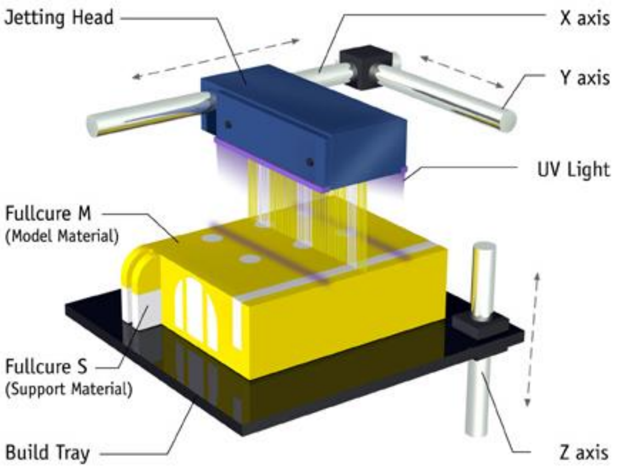


Figure 2. The principle of *PolyJet Matrix* method [Proto 3000 2013]

The samples for our research were manufactured by means of Stratasys Dimension SST 768 printer for the FDM method (Figure 3) and Objet Connex 500 for *PolyJet Matrix* (Figure 4).

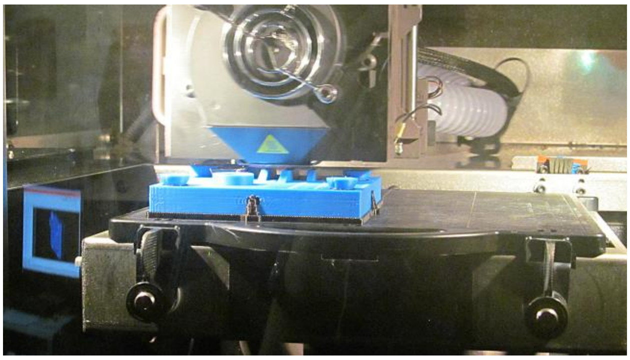


Figure 3. Model production using Dimension SST 768 3D printer

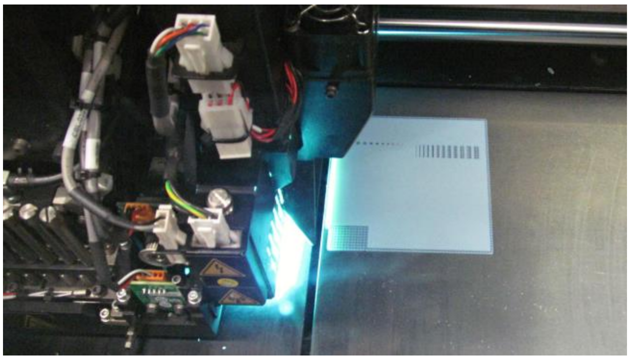


Figure 4. Model production using Objet Connex 500 3D printer

The technical parameters of the printers used are listed in the following tables.

Stratasys Dimension SST 768 [Stratasys 2007]	
Net build size	203 x 203 x 305 mm
Layer thickness	0.254 or 0.330 mm
Typical accuracy	± 0.127 mm

Table 1. Parameters of Stratasys Dimension SST 768 3D printer

Objet Connex 500 [Objet 2011]	
Net build size	490 x 390 x 200 mm
Layer thickness	0.016 or 0.030 mm
Typical accuracy	0.020 to 0.085 mm

Table 2. Parameters of Objet Connex 500 3D printer

3 MANUFACTURING THE TEST SAMPLES

Although there is no standard for testing the dimension and geometrical accuracy of parts manufactured by means of additive technologies, an own model based on research and prior experience [Šafka 2015] was designed. The base of the model is 100 × 100 mm, the sides of the base are fitted with M6 threads allowing mounting to a measurement equipment. The model contains shapes for inspection of basic dimensions, i.e. lengths, distances, angles and diameters of spherical and cylindrical surfaces. Geometry of the model was designed so that it contains as many problematic parts as possible. The key parts were inclined planes, identical cylinders in two different orientations, overhanging plane and three identical spheres. In addition, it is possible to inspect some deviations of shape and position, such as flatness, parallelism, concentricity of cylindrical surfaces, perpendicularity, etc. It is also possible to evaluate small details. For that purpose, the model is fitted with tiered rectangular through-grooves and circular holes (Figure 5). Distance and size of each of the geometrical object was selected with regard to the 3D scanning performed in the future. It is appropriate to place he objects so they do not unnecessarily overlap each other.

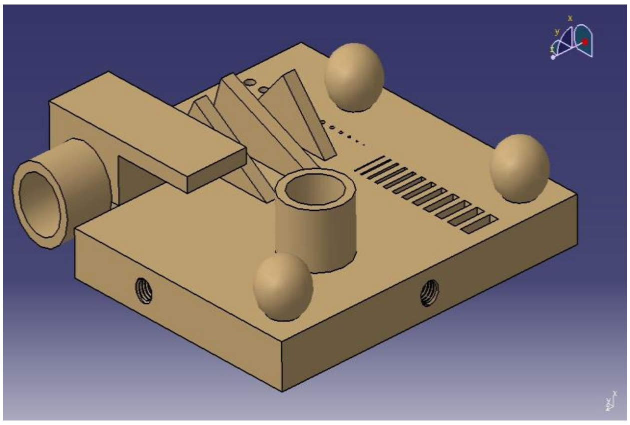


Figure 5. The designed CAD model

The diagram of inspected values is shown on the following figure 6.

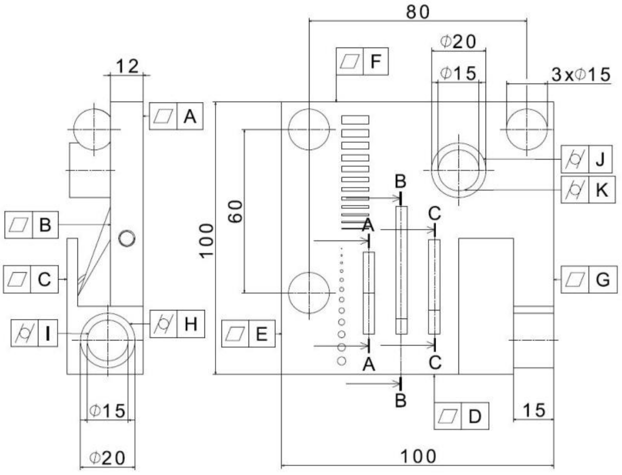


Figure 6. A diagram of the model with marked inspected elements and dimensions

For the model manufactured by means of *PolyJet Matrix* method, *VeroGray RGD850* material was used (manufacturer Stratasys, tensile strength 50 - 64 MPa, modulus of elasticity 2000 - 3000 MPa, flexural strength 75 - 110 MPa, flexural modulus 2200 - 3200 MPa, Shore hardness 83 - 86 Scale D - more information [Stratasys 2016]), while the layer thickness was set to both, 16 microns (referred to as HQ – *High Quality*) and 30 microns (referred to as HS – *High Speed*). In case of FDM technology, the most common material was used – ABS-P400 (manufacturer Stratasys, tensile strength 22 MPa, modulus of elasticity 1627 MPa, flexural strength 41 MPa, flexural modulus 1834 MPa – more information [Dimension 2011]), while the construction height was constantly 250 microns. Furthermore, a required type of *Sparse* support was selected. In case of FDM printing, *Solid* or *Sparse High* (Figure 7) construction materials with high material density was chosen. The structure of *Solid* offers full internal structure, while on the contrary, the *Sparse High* enables forming a lightweight internal structure, leading to decrease of construction material consumption and shortening the time necessary to print the model.

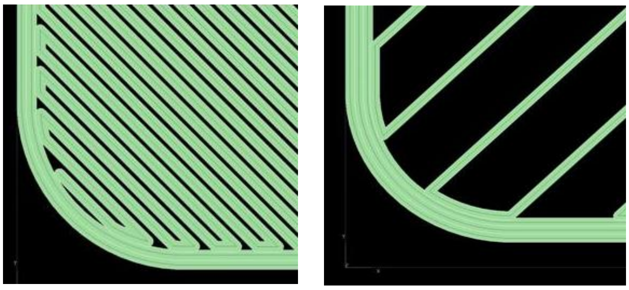


Figure 7. Structure of Solid (left), structure of Sparse High (right)

In total, we manufactured 4 types of models. Two models created using the FDM method with difference internal structure and two models created by means of the *PolyJet Matrix* with various thickness of the applied layer. The following table shows the comparison of individual technologies regarding the printing time and consumption of model and supporting material.

	Layer thickness	*Print time*	*Model material*	*Support material*
FDM Sparse	250 µm	5:43 h	54 cm^3	13 cm^3
FDM Full	250 µm	08:27 h	138 cm^3	13 cm^3
Objet HQ	16 µm	04:24 h	237 g	82 g
Objet HS	32 µm	02:20 h	226 g	75 g

Table 3. Comparison of individual technologies for 3D printing of samples

4 MEASUREMENT METHODS AND EQUIPMENT USED

In order to determine the influence of the construction technology and the selected parameters for 3D print on the geometrical and dimension accuracy of the samples, it was necessary to measure these models in a complex manners and subject the results to a thorough analysis. Using the experience from previous projects in [Mendřický 2014], a contact-less optical measurement method was used, since it offers several significant advantages in comparison to conventional ones. For example, due to its high data density, it allows obtaining an actual 3D model with high accuracy, even if the object is of a complex shape.

Digitisation of all the samples was performed by GOM – *ATOS II 400 3D* contact-less scanner fitted with an optic element with measurement volume 250 × 200 × 200 mm (Figure 8). This device uses principles of optical triangulation, photogrammetry and Fringe Projection method for calculation of coordinates in space. Stripes of light are projected onto the object surface (Figure 9), which are scanned by means of two CCD chip cameras. Maximum measuring error of this device is according Acceptance test 0.02 mm at the whole measuring volume [GOM MBH 2012_b, Frkal 2016].

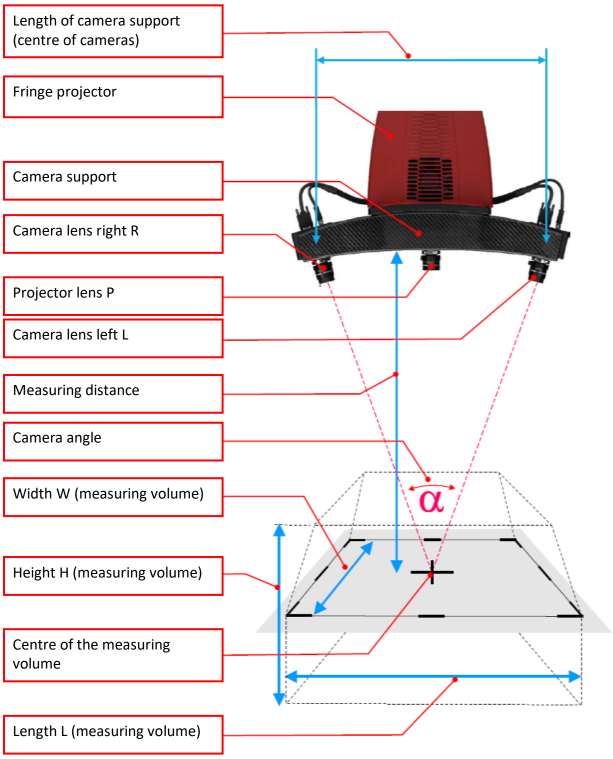


Figure 8. Definition of measurement volume of ATOS II 400 [GOM MBH 2012] optical scanner

Before the scanning process itself, the object was appropriately fitted with so called reference points (Figure 9). The purpose of these points is to transform individual scans into a global coordinate system. During the scanning process, the model was attached to a rotary table and a measuring device. The model was then scanned by performing approximately 40 images from various positions and angle so that the scans cover the whole surface of the model. The next step was a calculation of a high-resolution optimised polygonal mesh and evaluation using *GOM Inspect Professional v8* inspection software.

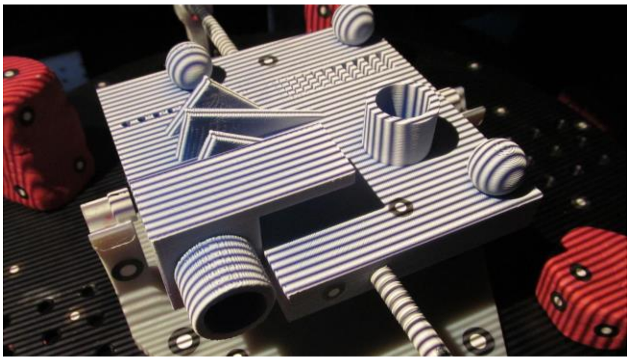
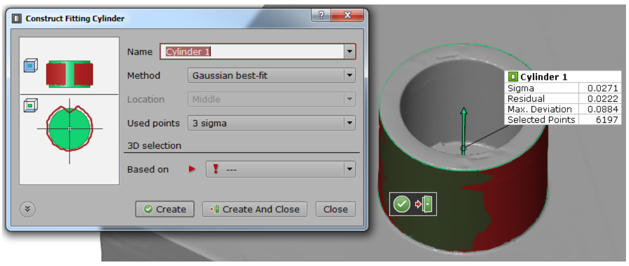


Figure 9. The digitisation process of the inspected sample

5 ANALYSIS OF MANUFACTURING ACCURACY

Firstly, an analysis of dimensional accuracy was performed. The analysis consisted of inspecting the diameters of spherical and cylindrical surfaces, length dimensions or spacing of the individual elements. Basic geometrical elements (cylinders, spheres, planes, etc.) were calculated by interlacing the fitting elements with Gauss BestFit for 3σ (Figure 10). In addition to outer and inner diameters, the cylindricity of the horizontal and vertical cylinder was evaluated as well.

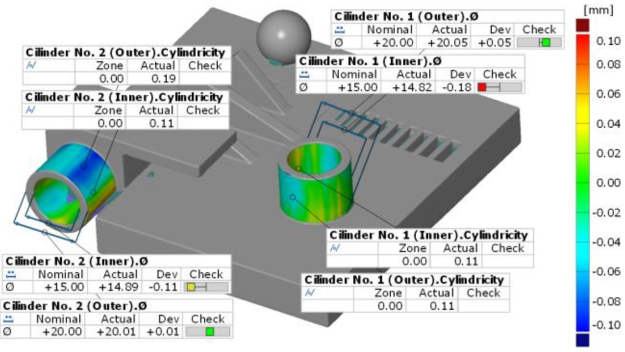


Name: Cylinder 1
Method: Gaussian best-fit
Location: Middle
Used points: 3 sigma
3D selection
Based on: ---

Cylinder 1	
Sigma	0.0271
Residual	0.0222
Max. Deviation	0.0884
Selected Points	6197

Figure 10. Construction of fitting outer cylinder

The Figure 11 shows an example of evaluation of a cylindrical elements on one of the samples, specifically the sample manufactured using Objet Connex 500 with layer thickness of 16 microns (Object HQ sample). Deviations from the nominal diameter of 20 mm or 15 mm for all of the models are summarised in Table 4, the cylindricity error are listed on the Figure 12.



Cilinder No. 1 (Outer).Ø

	Nominal	Actual	Dev	Check
Ø	+20.00	+20.05	+0.05	🟩

Cilinder No. 1 (Inner).Ø

	Nominal	Actual	Dev	Check
Ø	+15.00	+14.82	-0.18	🟥

Cilinder No. 2 (Outer).Cylindricity

	Zone	Actual	Check
	0.00	0.19	

Cilinder No. 2 (Inner).Cylindricity

	Zone	Actual	Check
	0.00	0.11	

Cilinder No. 1 (Inner).Cylindricity

	Zone	Actual	Check
	0.00	0.11	

Cilinder No. 2 (Inner).Ø

	Nominal	Actual	Dev	Check
Ø	+15.00	+14.89	-0.11	🟨

Cilinder No. 1 (Outer).Cylindricity

	Zone	Actual	Check
	0.00	0.11	

Cilinder No. 2 (Outer).Ø

	Nominal	Actual	Dev	Check
Ø	+20.00	+20.01	+0.01	🟩

Figure 11. Inspection of cylindricity and inner and outer diameters (Objet HQ)

Deviation [mm]	***No. 1 (inner)***	***No. 1 (outer)***	***No. 2 (inner)***	***No. 2 (outer)***
FDM Sparse	- 0.03	- 0.09	- 0.05	- 0.04
FDM Full	- 0.04	- 0.06	- 0.13	- 0.10
Objet HQ	- 0.19	+ 0.05	- 0.11	+ 0.01
Objet HS	- 0.28	- 0.04	- 0.14	- 0.08

Table 4. Deviations from the nominal cylinder diameters

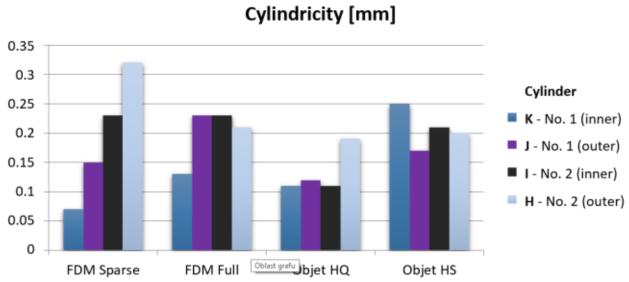


Figure 12. Cylindricity of inner and outer cylinders

At first glance, the results imply that the diameter deviations of cylindrical elements manufactured by *Stratasys Dimension SST 768* ranged within the tolerances provided by the printer manufacturer. The deviations of inner and outer cylinder diameters were almost identical. Therefore a statement can be made – the cylinder orientation does not affect the dimension accuracy of its surface.

Unfortunately, such statement cannot be made for the case of models built by *Object Connex 500*. The only diameters Connex managed to keep within the limit dimensions were outer diameters of the cylinders. Diameters of the inner cylinders were significantly smaller than the nominal dimensions. The actual deviation was negative and ranged from - 0.11 to - 0.28 mm. There might be a certain influence of difficult removal of supporting material in case of these hard-to-reach spots.

Another inspected geometry were diameters of spherical elements, their spacing, and absolute dimensions of the sample, specifically their width in direction of X- and Y-axis and height in Z-axis. It is the pitch distance of individual spheres that best shows, with what accuracy can the printer work in individual coordinate axes. When measuring spacing, the resulting dimension is not affected by eventual error of the given element, and the eventual negative impact of the anti-reflection coating for 3D scanning is eliminated. The inspection of absolute width showed that the samples printed by *PolyJet Matrix* method with the HS setting are significantly smaller when compared to the nominal dimension (see DX and DY dimensions in Table 5). The deviation ranged from -0.24 to -0.32 mm. When set to *High Quality*, the dimensions of the model were within the declared accuracies provided by the manufacturer.

Deviation [mm]	***DZ***	***DY***	***DX***	***S1-S2***	***S2-S3***	***S1***	***S2***	***S3***
FDM Sparse	+0.24	+0.04	0.00	+0.03	0.00	-0.11	-0.12	-0.12
FDM Full	+0.26	+0.09	+0.01	+0.06	0.00	-0.11	-0.11	-0.11
Objet HQ	-0.09	-0.11	-0.10	0.01	-0.05	+0.04	+0.06	+0.07
Objet HS	-0.05	-0.32	-0.24	0.00	-0.10	-0.05	+0.01	0.00

Table 5. FDM, Object: Deviations from the nominal dimension (absolute dimensions, spacing of spheres, diameters of spheres)

The samples created using the FDM technology were not affected by the construction settings and managed to keep within the declared accuracies in X- and Y-axis. A problem occurred when measuring in vertical direction (Z-axis) where both FDM models significantly exceeded the top limit dimensions. This issue is proven by the following graph (Figure 13) that forms an overview of deviations of inspected dimensions in the FDM samples. The results of both technologies are summarized in Table 5.

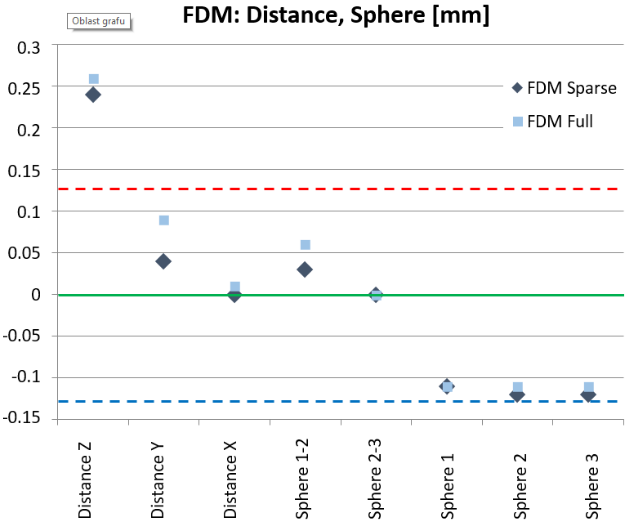


Figure 13. FDM: Deviations from the nominal dimension (absolute dimensions, spacing of spheres, diameters of spheres)

In case of *PolyJet Matrix*, the dimensions of spherical elements were within the required tolerance values, while the error of the FDM samples ranged on the lower tolerance limit. The maximum error of sphere spacing occurred in the *Object HS* sample, specifically between spheres No. 2 and No. 3 (i.e. X-axis dimension), which was - 0.1 mm. In all other samples, the deviation did not exceed 0.06 mm.

The dimensional parameters are undoubtedly important, however, they may not always mean that the product shape conforms to the nominal CAD model. If more information regarding shape accuracy of printed models are required, it is vital to use so called GD&T analysis. In our project, we focused mainly on inspection of flatness of horizontal, vertical and sloped surfaces. Here, we identified significant errors, mainly in case of large horizontal surfaces (Figure 6, marked A and B). The flatness error values for FDM samples ranged in tenths of a millimetre. It was confirmed that in case of FDM technology, the model is being deformed mainly in the plane of the table, which may be caused by material cooling and occurrence of internal tension. In order to illustrate such conformity with the nominal CAD model, we performed a calculation of normal deviation of the real (measured) model against the nominal (CAD) model in all its parts. In order to do such operation, we used the 3D optical digitization method. Such evaluation is very complex, objective and often helps to quickly and effectively expose a problem in the manufacturing process. For the purpose of this analysis, the model was aligned using the Best Fit method (sum of squared deviations of all points of the real model from a CAD model is minimal) to a CAD model, while the calculated magnitude of normal deviations was displayed by means of a colour spectrum (Figure 14).

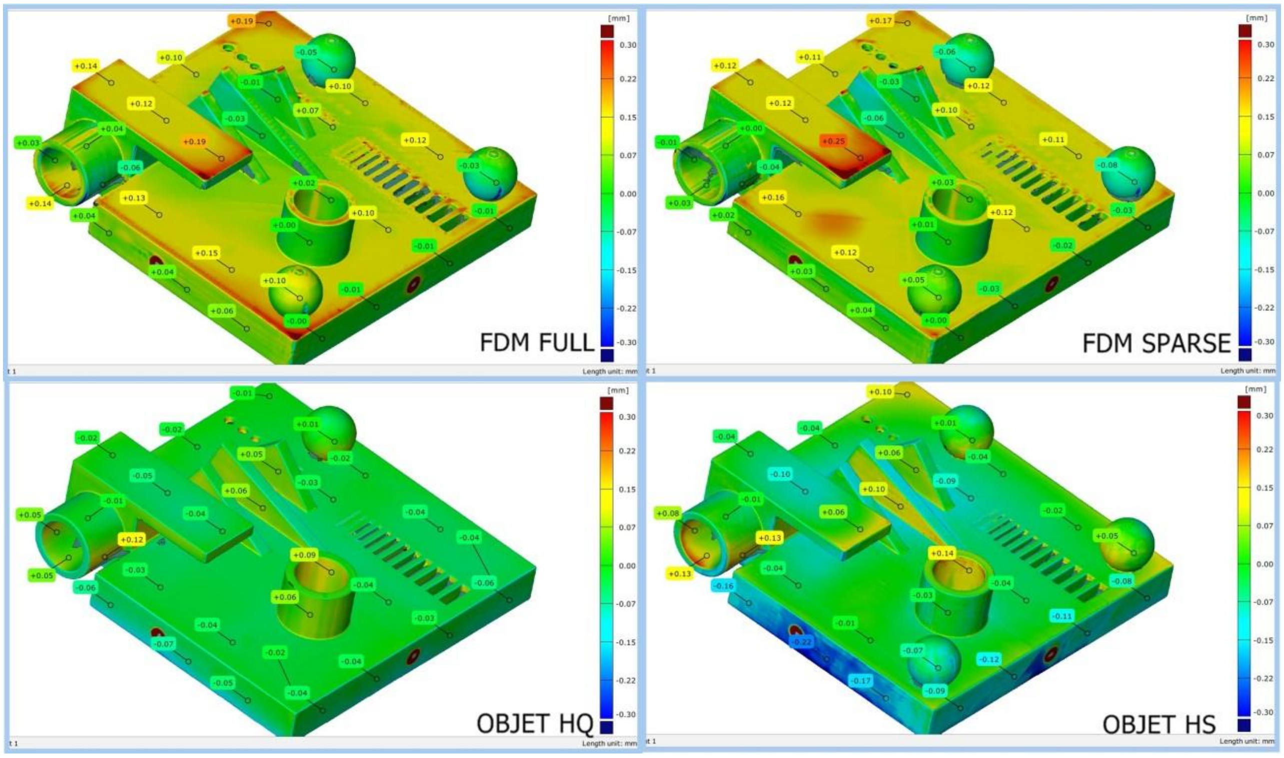


Figure 14. Colour map of normal deviations

As the analysis shows, the highest accuracy was reached by *Object Connex 500* with the HQ setting – 16 µm layer thickness. The printed manufacturer states that the construction accuracy should range between 0.02 and 0.085 mm depending on used material, geometry of individual parts, model orientation and settings of construction parameters. This requirement was met on most cases. Unfortunately, the *Object HS* failed to keep within the tolerance for construction accuracy. Analysis of deviations confirmed the same problem with the outer dimensions of the model. As the Figure 14 imply, the horizontal planes show a significant negative deviation (blue colour) that is, in most cases, higher than - 0.1 mm. Width of the model is therefore smaller than it should be.

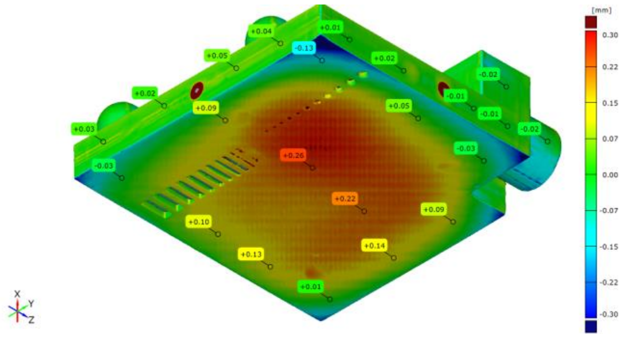


Figure 15. Colour map of normal deviations (FDM Full)

The results of analysis of *FDM* samples show that deviations from the CAM model are overall higher than in case of the samples printed by means of *PolyJet Matrix*. The declared tolerance of construction accuracy provided by the manufacturer of this printer is 0.127 mm. From the *FDM* sample analysis we see that this condition was not always met, while the most significant errors are apparent on horizontal planes. This phenomenon is most visible on the bottom side of the model (*FDM Full* – see Figure 15), where the surface is significantly convex. And again, the measurement proved that the thickness of FDM samples is higher.

Summary:

- Stratasys Dimension printer (FDM)
  - the absolute dimension in vertical axis is higher
  - sphere diameters are smaller
  - the *Full* and *Sparse* print settings did not affect the accuracy in any significant way
- *Object Connex 500* printer (*PolyJet Matrix*) prints with higher accuracy than the Dimension, however, it did not keep within the values provided by the manufacturer
  - diameters of inner cylinders are smaller
  - absolute dimension in horizontal directions are smaller
  - deviations in HS setting are higher than in HQ setting

6 CONCLUSION

The main goal of this research was to perform accuracy analysis of additive methods of parts manufacturing depending on the used Rapid Prototyping technology and to compare the accuracy data provided by the manufacturers.

It turned out that sometimes, we cannot rely on printing accuracy parameters given by the printer manufacturers. The *Objet Connex 500* declares accuracy from 0.02 to 0.085 mm, depending on many factors that are, however, not specified. The value of 0.085 mm was considered to be a limit dimension. This value was repeatedly exceeded, especially with the *High Speed* setting, where the layer thickness is 30 µm. The limit was exceeded mainly when inspecting the absolute dimension in the horizontal plane, where a significant negative deviation was detected. The reason for that might be a shrinkage of material, since when manufacturing a model in a HG mode, where each applied layer is being rolled, while in HS mode rolls every second layer. Additionally, the shrinking affects the applied pressure and cooling rate of the model.

The manufacturer of Stratasys *Dimension SST 768* provides printing accuracy of 0.127 mm. The exceedance of this tolerance was detected mostly in absolute nominal dimension of vertical Z-axis. However, that may be a result of layer rounding (multiples of 0.25 mm). As the surface comparison with the CAD model showed, the overall deformation of the model was an even bigger issue. This deformation is probably caused by internal tension resulting from material cooling. The overall model deformation may also be affected by for example using supports with better quality, performing controlled model cooling, or changing the orientation of the model within the printer's work area.

Manufacturing of parts using the 3D printing technologies is recently on a steep rise, however, in most cases, the printed parts are incomparable with the parts manufactured using traditional methods in terms of accuracy and quality. Complex quality evaluation of parts manufactured by means of 3D printing is therefore of high value in practice, since when ensuring manufacturing with a certain quality and accuracy, one must know the specific limitations of the given technology.

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