

THE ACCURACY AND THE PRINTING RESOLUTION COMPARISON OF DIFFERENT 3D PRINTING TECHNOLOGIES

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Abstract

The article presents a research conducted with the project: ‘Additive technology used in conduction with optical methods for rapid prototyping of 3D printed models’ [13]. In this article selected three different 3D printing technologies: Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Material Jetting (MJ). Each of them was tested paying special attention to accuracy and resolution of printed elements. Accuracy tests were conducted on the reference specimens which also showed material texture. These specimens were scanned to verified dimensional deviations of printing methods. Printing resolution was verified on a heat exchanger model which was characterized by complicated structure. The highest accuracy and printing resolution was noticed in the MJ technology, PolyJet method on the Objet Eden 260 VS printing machine and the SUP 707 water soluble support material.

Keywords: 3D printing, accuracy, printing resolution, complicated shapes.

1. INTRODUCTION

The purpose of this article was selected a technology and a material from three different 3D printing methods with the highest accuracy and printing resolution. Moreover, there were considered cost of machine, materials and service costs. The revision was created in particular to analyse of complicated shapes by the best parameters for each 3D printing method for the accessible printing machines. These technologies were typed considering literature and information contained in manufacturer brochures. Nonetheless, the aim this article is not only theoretical considering about this method but using the best practise.

2. 3D PRINTING METHODS

2.1. FDM technology

Based on the information from [1,7,8] the FDM technology is the most common due to price and simplicity. The FDM uses extruded polymer from heated head printer and impose it layer by layer. Afterwards polymer harden itself. The printing process takes place in a heated chamber to avoid material shrinkage and shape deformations. A support material is provided from another printer head and leach out after the printing process. A filament is rolled up on an interchangeable coil. The most common materials are ABS (acrylonitrile butadiene styrene) and PLA (polylactide).

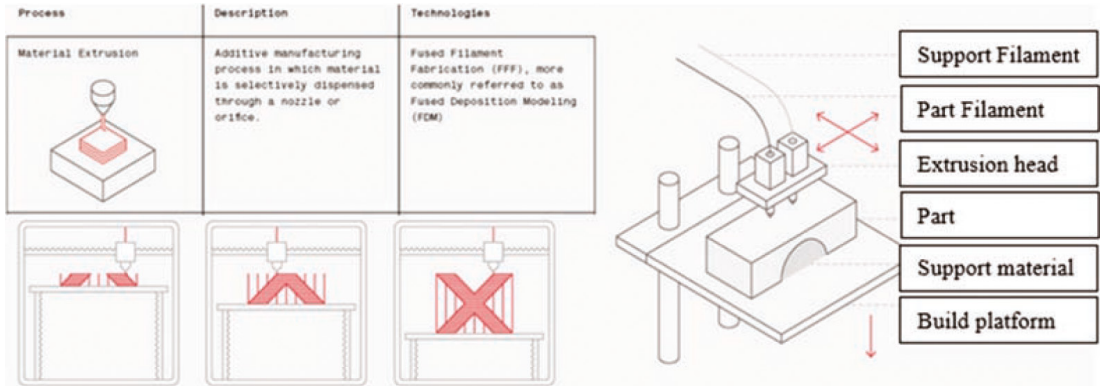


Figure 1. The FDM printing process and schematic of the printer [2]

2.2. SLS technology

The SLS is the 3D printing technology were used laser to sinter powder material [3,6,8]. A model is built in the heated chamber filled with a powder material which is both main and support material. The most common powders are PA12 (polyamide) and PS (polystyrene). A support material is removed by compressed air. This method is mainly used to low-volume production.

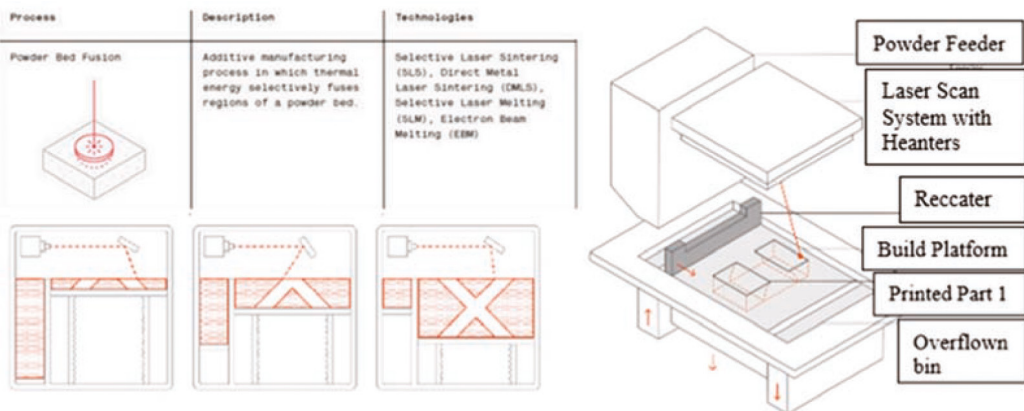


Figure 2. The SLS printing process and schematic of the printer [2]

2.3. Material Jetting technology

The MJ technology [4,5,12] includes two main methods: the PolyJet from Stratasys and the ProJet from 3DSystems. Both methods use UV light to cure photopolymer extruded from the piezoelectric head in the shape of fine drops. A model is built from thin layers (16-32 μm). A support material is extruded from another part of head and can be removed using heat, hot water, oil or alkaline solution. The MJ technology has a wide range of polymers and it allows to mix them to create new digital materials which are characterised by different textures and properties. Moreover, this is one of the most accurate 3D printing method.

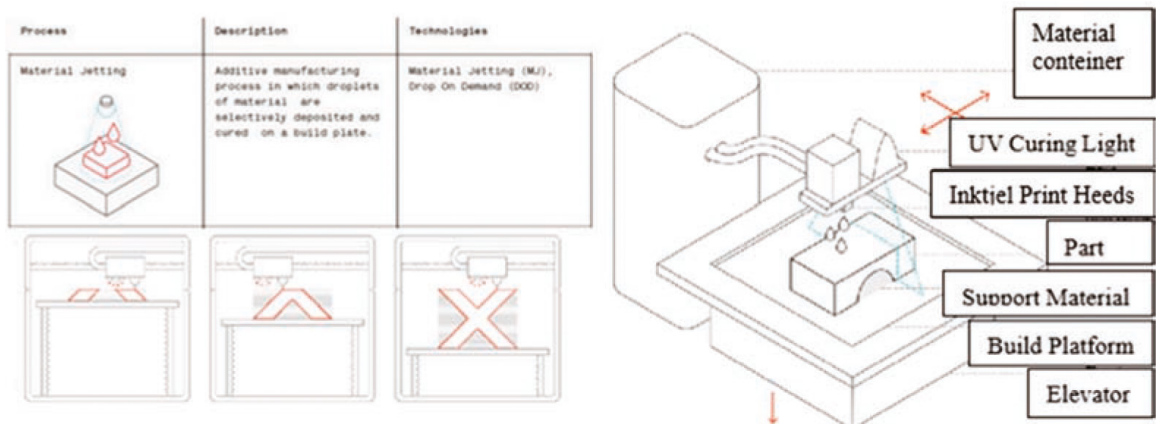


Figure 3. The MJ printing process and schematic of the printer [2]

3. COMPARISON OF ACCURACY

Each test was conducted on three specimens in two different specimens' shape. Next, the specimens were scanned using the 3D Steinbichler Comet L3D scanner with nominal measurement accuracy of machine equal to 10 μm . Specimens scans were superimposed on the 3D model from a CAD software to verify a dimensional deviation of printed specimens.

3.1. Geometric analysis – FDM technology

The first step was to test specimens in the FDM technology [9]. The reference specimens were printed on the Fortus 250mc machine produced by the Stratasys company. Models were able to print in 0.330 mm, 0.254 mm or 0.178 mm thicknesses. The nominal printing machine accuracy is ± 0.241 mm. Three dumbbell specimens (see Figure 4) and three rectangular prism specimens with hole (see Figure 5) were printed with a different nominal layer thickness (0.254 mm and 0.178 mm) [11]. All scan results were gathered in Table 1 and demonstrate on the pictures below (see from Figure 6 to Figure 9). It was noticed for all specimens that one of the biggest flat surfaces is more deformed than other ones.



Figure 4. Printed dumbbell specimen (high: 210 mm)



Figure 5. Printed rectangular prism with hole specimen (high: 210 mm)

Table 1. The minimum and maximum accuracy deviation of dumbbell specimen printed with different thickness layer in FDM technology

FDM technology nominal accuracy $\pm 0,241$ mm	Dumbbell specimen layer thickness 0.178 mm	Dumbbell specimen layer thickness 0.254 mm	Rectangular prism with hole specimen layer thickness 0.178 mm	Rectangular prism with hole specimen layer thickness 0.254 mm
Maximum deviation [mm]	+0.163	+0.346	+0.205	+0.353
Minimum deviation [mm]	-0.160	-0.298	-0.359	-0.198

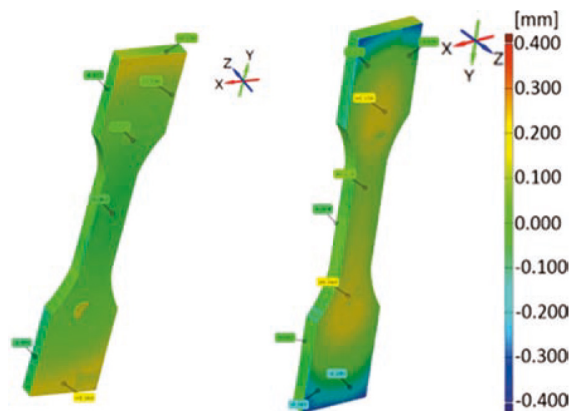


Figure 6. The dumbbell specimen scan printed with nominal layer thickness 0.178 mm (FDM)

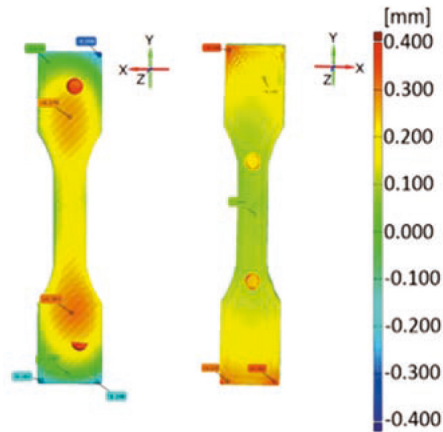


Figure 7. The dumbbell specimen scan printed with nominal layer thickness 0.254 mm (FDM)

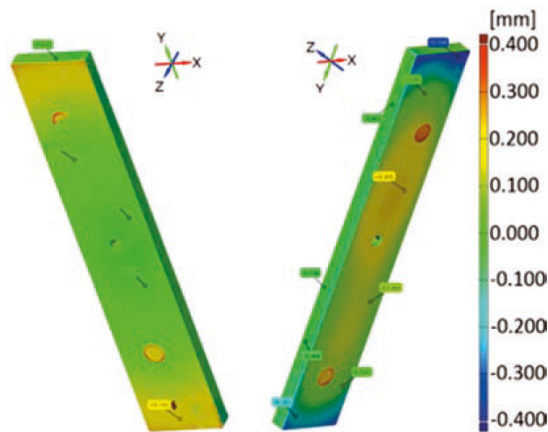


Figure 8. The rectangular prism with hole specimen scan printed with nominal layer thickness 0.178 mm (FDM)

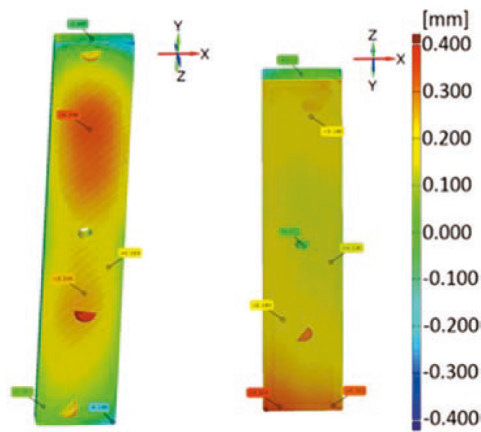


Figure 9. The rectangular prism with hole specimen scan printed with nominal layer thickness 0.254 mm (FDM)

The following phase in an investigation was to check an accuracy of three-dimensional specimens after tests on the flat ones. It was printed one cylinder (Figure 10) and one bionic specimen (Figure 11) and an air turbine head specimen. The specimens were printed with the nominal layer thickness 0.254 mm on the same printer as the flat specimens. All results are gathered in Table 2.



Figure 10. The printed three-dimensional cylinder specimen (high: 160 mm)

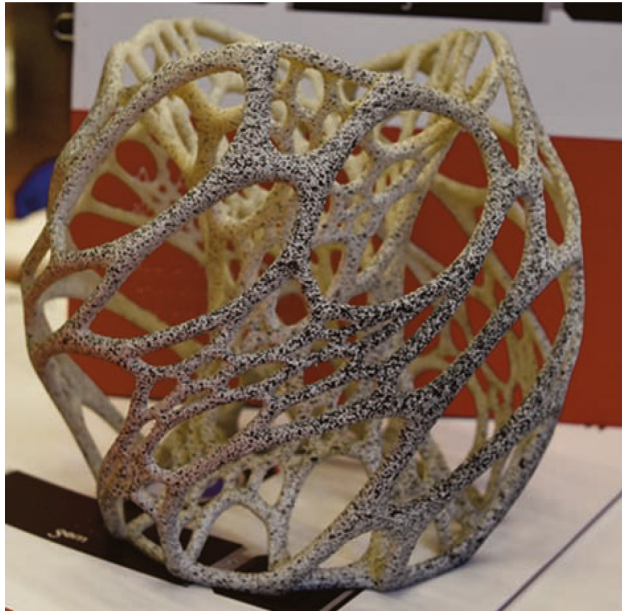


Figure 11. The printed three-dimensional bionic specimen (high: 130 mm)

For the cylinder specimen scan, the accuracy results were totalled between +0.372 mm and -0.200 mm on the cylinder root (Figure 12). The high dimensional deviation was occurred on the flat surface of cylinder (-0.228 mm) and a seam going along the whole specimen. The printed cylinder naked eye observations were nonhomogeneous, rugged surface. For the bionic specimen, the biggest dimensional deviation was occurred on the top specimen surface (-0.507 mm) (Figure 13). For the three-dimensional air turbine head specimen, the biggest dimensional deviation was totalled between +0.136 and -0.162 mm (Figure 14).

It was noticed that the models printed in FDM technology are characterized by some big areas with the high deformation; therefore, general dimensional accuracy equal to ca. ± 0.1 mm with some big areas with a lower accuracy up to ± 0.5 mm.

Table 2. The minimum and maximum accuracy deviation of space specimen printed in FDM technology

FDM technology nominal accuracy $\pm 0,241$ mm	Cylinder specimen layer thickness 0.254 mm	Bionic specimen layer thickness 0.254 mm	Air turbine head specimen layer thickness 0.254 mm
Maximum deviation [mm]	+0.372	+0.507	+0.136
Minimum deviation [mm]	-0.200	-0.227	-0.162

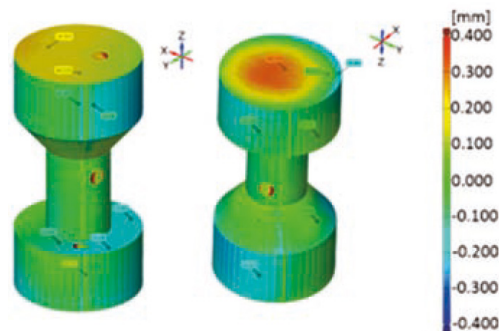


Figure 12. The three-dimensional cylinder specimen scan printed with nominal layer thickness 0.254 mm (FDM)

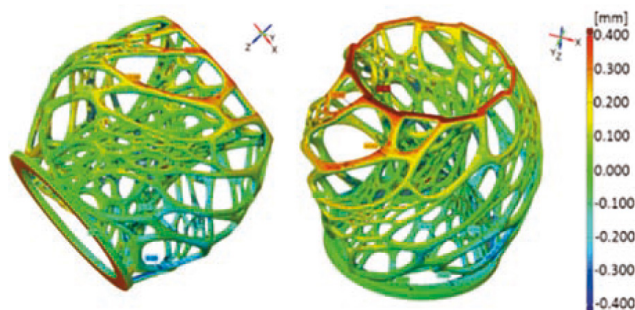


Figure 13. The three-dimensional bionic specimen scan with nominal layer thickness 0.254 mm (FDM)

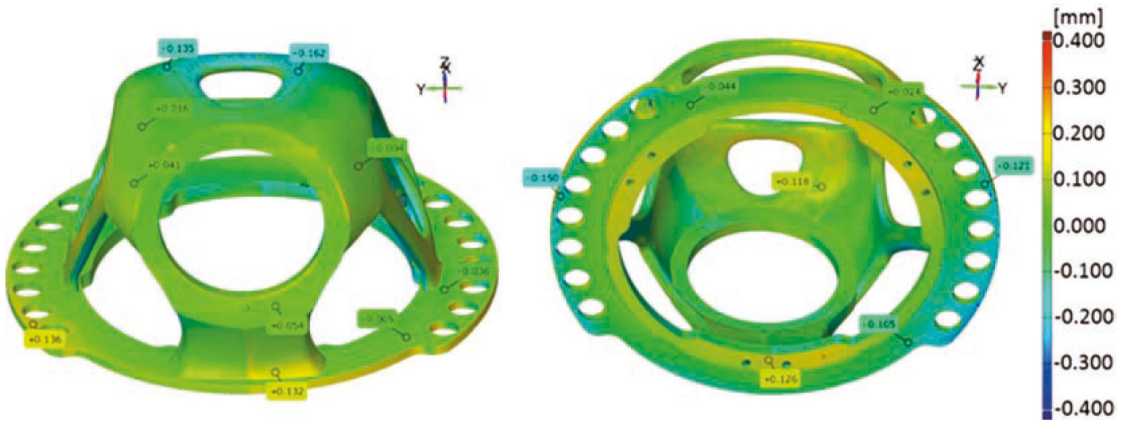


Figure 14. The three-dimensional air turbine head specimen scan with nominal layer thickness 0.254 mm (FDM)

3.2. Geometric analysis – SLS technology

The second step was to test both flat and three-dimensional specimens in the SLS technology (see Figure 15)[10]. The reference specimens were printed with 0.120 mm layer thickness on the EOSINT P 395 machine produced by EOS company. The nominal printing machine accuracy is ± 0.3 mm. All results are gathered in Table 3 and demonstrates on the pictures below (see from Figure 16 to Figure 18).



Figure 15. The dumbbell and rectangular prism with hole specimens printed in the SLS technology

For the dumbbell specimen, an accuracy results were between +0.201 mm and -0.359 mm and were detected in the similar areas as in the FDM (Figure 16). For the rectangular prism with a hole specimen, an accuracy results were between +0.221 mm on the specimen edges and -0.301 mm on the surface connected with the printing table (Figure 17). A deviation culmination was occurred in the same areas as for dumbbell specimen. For the air turbine head specimen, the biggest dimensional deviation was between +0.290 and -0.297 mm (Figure 18).

The common feature for all SLS printed specimens is general dimensional accuracy equal to ca. ± 0.05 mm with some areas with a lower accuracy up to ± 0.5 mm.

Table 3. The minimum and maximum accuracy deviation of the flat and three-dimensional specimens printed in the SLS technology

SLS technology nominal accuracy ± 0.3 mm	Dumbbell specimen layer thickness 0.120 mm	Rectangular prism with hole specimen layer thickness 0.120 mm	Air turbine head specimen layer thickness 0.120 mm
Maximum deviation [mm]	+0.372	+0.507	+0.290
Minimum deviation [mm]	-0.200	-0.227	-0.297

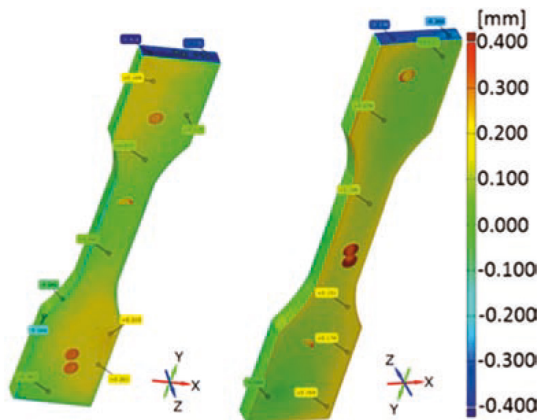


Figure 16. The dumbbell specimen scan printed with nominal layer thickness 0.120 mm (SLS)

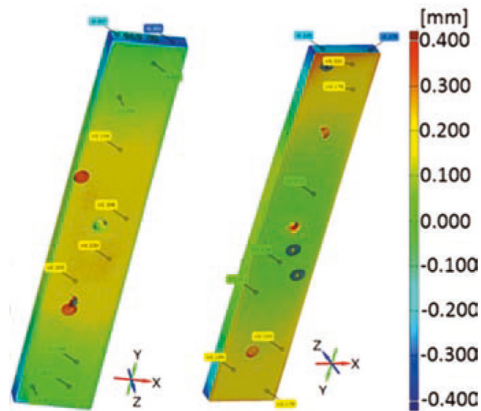


Figure 17. The rectangular prism with hole specimen scan printed with nominal layer thickness 0.120 mm (SLS)



Figure 18. The three-dimensional air turbine head specimen scan with nominal layer thickness 0.120 mm (SLS)

3.3. Geometric analysis – Material Jetting technology (PolyJet method)

The last step was to test flat and three-dimensional specimens in the MJ technology. The reference specimens were printed with 0.028 mm layer thickness in the PolyJet method on the Objet 30 Prime machine produced by Stratasys company. The nominal printing machine accuracy is ± 0.1 mm. Three dumbbell specimens and three rectangular prism specimens with a hole were printed (see Figure 19). All results are gathered in Table 4 and presented on the pictures below (see from Figure 20 to Figure 22).

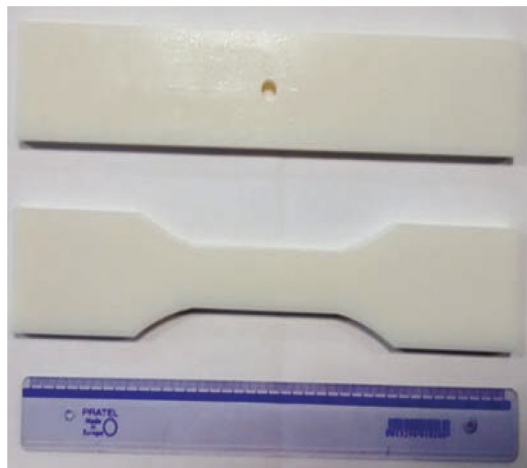


Figure 19. The dumbbell and rectangular prism with hole specimens printed in the Material Jetting (PolyJet) technology

For the dumbbell specimen, an accuracy results were between +0.045 mm and -0.010 mm, deviations were similar on all specimen surfaces (Figure 20). For the rectangular prism with a hole specimen, an accuracy results were between +0.065 mm and -0.029 mm. Deviations were also similar on all specimen surfaces (Figure 21). For the three-dimensional air turbine head specimen, the dimensional deviation was between +0.518 to -0.507 mm (Figure 22).

It was noticed that the FDM and the SLS technology printed models have much lower accuracy than the PolyJet method in the simple shape specimen. However, for the three-dimensional air turbine head specimen the lowest accuracy has PolyJet equal to ca. ± 0.5 mm.

Table 4. The minimum and maximum accuracy deviation of flat and three-dimensional specimens printed in MJ PolyJet technology

PolyJet method nominal accuracy ± 0.1 mm	Dumbbell specimen layer thickness 0.028 mm	Rectangular prism with hole specimen layer thickness 0.028 mm	Air turbine head specimen layer thickness 0.028 mm
Maximum deviation [mm]	+0.045	+0.065	+0.518
Minimum deviation [mm]	-0.010	-0.029	-0.507

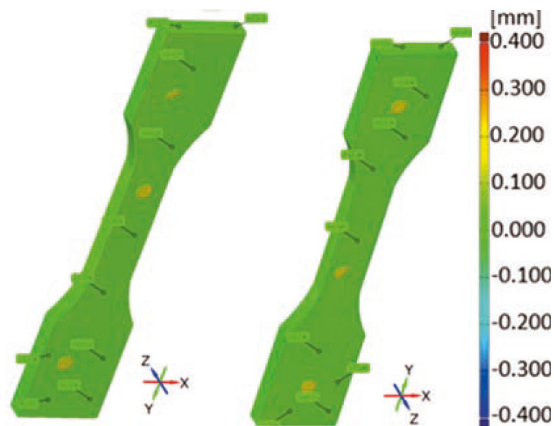


Figure 20. The dumbbell specimen scan printed with nominal layer thickness 0.028 mm (PolyJet method)

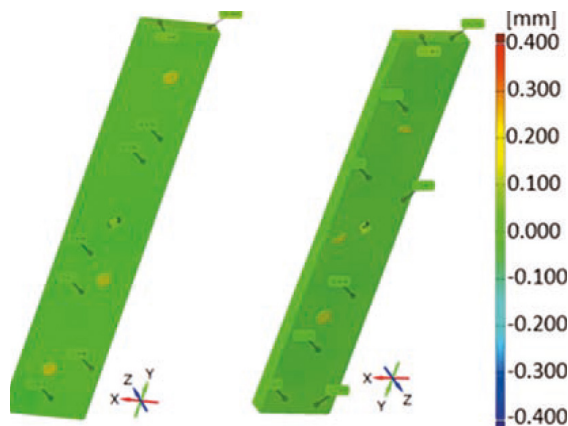


Figure 21. The rectangular prism with hole specimen scan printed with nominal layer thickness 0.028 mm (PolyJet method)



Figure 22. The three-dimensional air turbine head specimen scan with nominal layer thickness 0.028 mm (PolyJet method)

4. PRINTING RESOLUTION COMPARISON

The heat exchanger model (see Figure 23) was designed to verify printing resolution of three technologies - FDM, SLS and MJ [15]. Thin walls (0.91 mm) were arranged by turns with 2.71 mm space between them in an original size. The model was prepared in three different scales 1:1, 1:2 and 1:4 to check ability to print complicated shapes and easy remove of support.

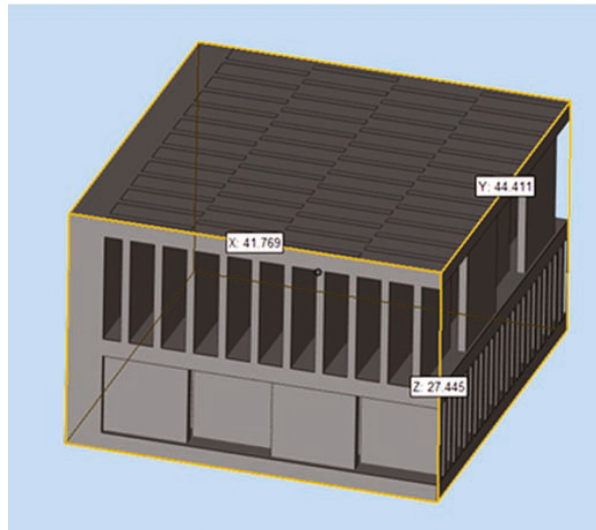


Figure 23. The heat exchanger model fragment in 1:1 scale (dimensions in mm)

Initially, the heat exchanger models were printed without use of support material in the FDM technology (see Figure 24). The model in 1:4 scale was printed with the lowest possible printer resolution (one layer of material) due to thicker walls compare to original one. A limited printer accuracy caused of warped walls. The heat exchanger model fragments in 1:2 and 1:1 scales collapsed under its own weight and further printing was impossible.

Next, the heat exchanger models were printed with a support material (see Figure 25). The heat exchanger models in both 1:1 and 1:2 scales were printed properly however some walls were nicked probably due to the printing errors. The heat exchanger model fragment in 1:4 scale was partially destroyed during the support removing. This support was not entirely removed due to the narrow distance between walls (0.68 mm). Figure 26 shows full-dimension heat exchanger in 1:1 scale. The support material was not also entirely removed due to the complicated shape of model which hinder proper support-remover flow.

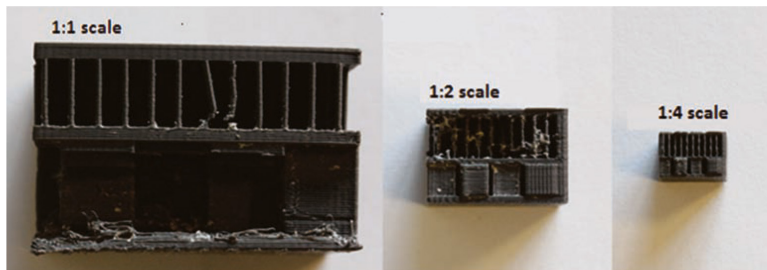


Figure 24. Fragments of the heat exchanger model printed in FDM technology (without support).

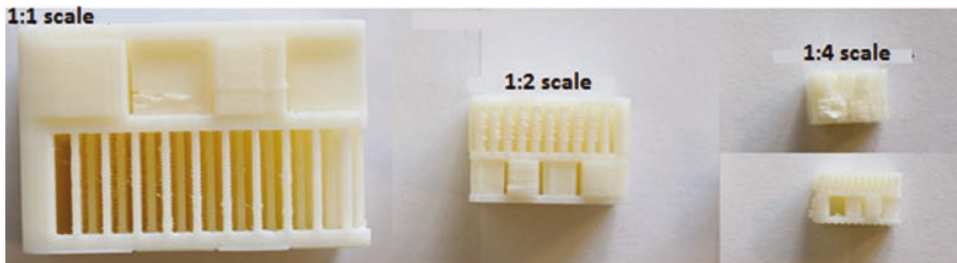


Figure 25. Fragments of the heat exchanger model printed in FDM technology (with support).



Figure 26. The heat exchanger model printed in 1:1 scale in FDM technology (with support)

The following step was printed the heat exchanger in three scales in the SLS technology (see Figure 27). There is the same material for both model and support; therefore, there is no possibility to control the support build process.

The full-dimension heat exchanger was properly printed without any destroyed walls (see Figure 28). The support material was easily removed from the model in scales 1:1 and 1:2 however a support-powder left inside the model – powder was partially baked in the closed or hard to reach spaces what cause support-remove issues, whereas 1:4 scale model was completely baked.

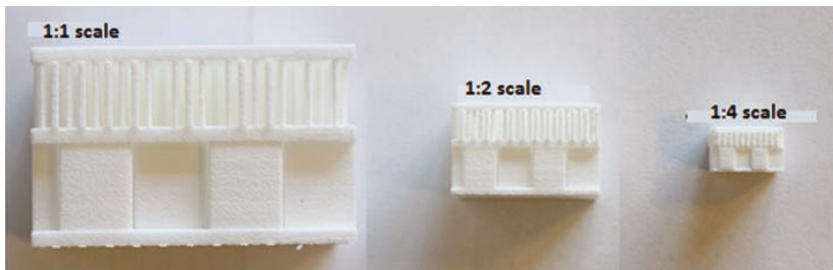


Figure 27. Fragments of heat exchanger model printed in the SLS technology

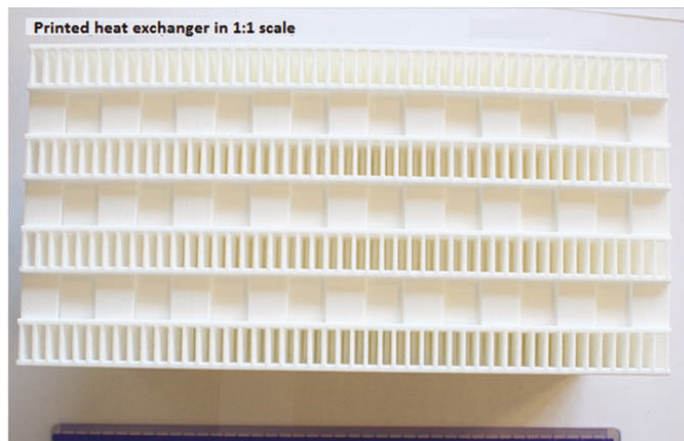


Figure 28. The heat exchanger model printed in 1:1 scale in the SLS technology

The last one was printed the heat exchanger in the MJ technology, PolyJet method. This method provides three supports materials removed by different fluids: SUP 705 – removed using water under pressure, SUP 706 – soluble using solvent, SUP 707 – soluble using still water. Both SUP 705 and 706 encounter a similar difficulty during remove process as in the SLS technology (see Figure 29) [14]. The model shape for 1:1 and 1:2 scales was properly imaged whereas in the model for 1:4 scale was hard to detect walls and spaces between them– this model was filled out with support material. SUP 707 material was removed from models in each scale with saved shape and lack of errors (see Figure 30).

Afterwards, the proper full-size heat exchanger was printed using VeroClear and VeroWhite Plus material with SUP 707 support material. Figure 31 demonstrates the model printed in VeroClear material with lack of support material inside the model.

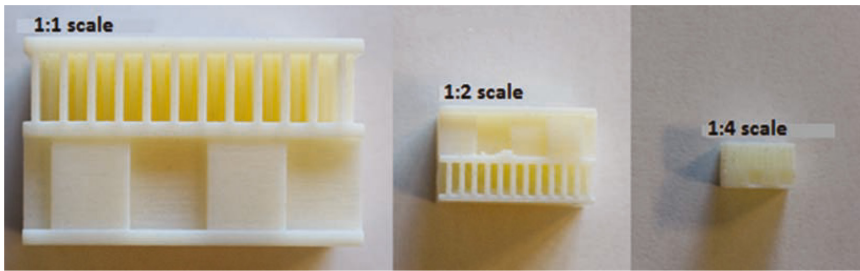


Figure 29. Fragments of the heat exchanger model printed in the PolyJet method (SUP 706 support)

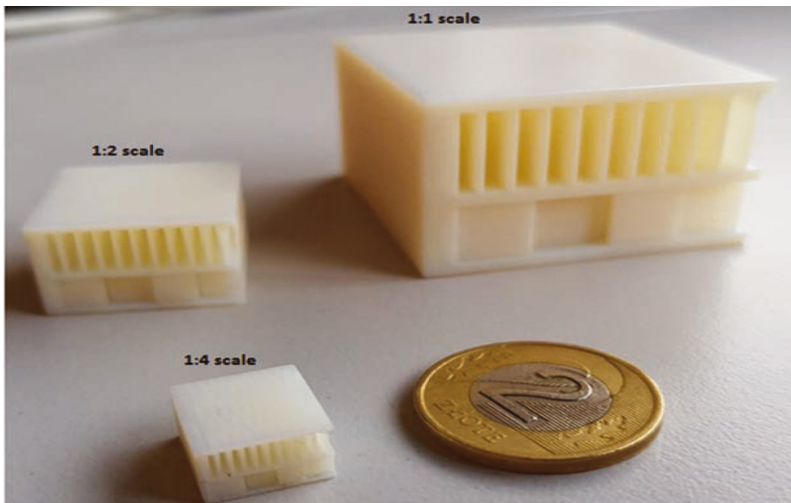


Figure 30. Fragments of the heat exchanger model printed in the PolyJet method (SUP 707 support)



Figure 31. The heat exchanger model printed in 1:1 scale in the PolyJet method (SUP 707 support)

5. SUMMARY

The primarily purpose of this article was to select the technology and material from three different 3D printing methods with the highest accuracy and printing resolution. The main aspects were considered as an accuracy and resolution however cost of machine, materials, service costs and time were also reflected. The conclusions were gathered in Table 5. The revision was created in particular to analyse of complicated shapes by the best parameters for each 3D printing method for the accessible printing machine; therefore, for printing process were used the minimal thickness of layers for each method for the concrete 3d printing machine (not the same thickness for all). The stair effect is unmentioned due to ensure smooth surfaces by using the minimal thickness of printing layer [16]. The FDM technology provided a low machine and an exploitation cost in acceptable time however printed models were characterized by comparable accuracy and resolution in variety shapes. The SLS technology provided higher accuracy and resolution of models however, long pre-processing and post-processing time or low-volume production type were made this technology quite expensive for piece production. The Material Jetting technology (PolyJet method) were characterized by high accuracy and resolution of printed models especially for simple shapes. Moreover, MJ has rapid and average cost of printing single models and user-friendly printing machine.

Geometric analysis of the reference specimens demonstrated meaningful difference between the FDM, SLS and MJ technologies. It was concluded, printed models in the FDM technology were characterized by some big areas with high deformation. For all FDM printed specimens, the common feature was general dimensional accuracy equal to ca. ± 0.1 mm with some big areas with a lower accuracy up to ± 0.4 mm. For all SLS printed specimens, the common feature was general dimensional accuracy equal to ca. ± 0.05 mm with some areas with lower accuracy up to ± 0.5 mm. Presuming, as a production result that printed models in the FDM and SLS technology had much lower accuracy than the MJ technology (PolyJet method) for the simple shapes. For PolyJet printed specimens, the common feature was uniform surface deviation localization with general dimensional accuracy equal to ca. ± 0.05 mm. However, for more complex shape like the air turbine head specimen were noticed some small areas with lower accuracy up to ± 0.5 mm.

Printing resolutions were verified on the complicated shape printed in the different scales; therefore, it was discovered that variety of the support material and its removing method have a meaningful influence on the shape and quality of the printed model. For the FDM technology models were observed printing errors on the walls and support material was hard to remove in 1:4 scale and full-size models. For the SLS technology model, powder is build and support material in the same time and support powder were able to bake to the model in the closed or hard to reach spaces due to support-remove problems.

Nowadays, the matter of accuracy and the printing resolution comparison is extensively described in the studies of various centres, both domestic and foreign. Almost of the investigations have not released yet. In summary, the PolyJet method with SUP 707 material solely allows to achieve the proper complicated models with thin walls and narrow spaces between them in each scale and size in this review.

Table 5. Comparison of the 3D printing technologies

	FDM	SLS	Material Jetting (PolyJet)
Homogeneous of printing models	low	average	high
Thin wall models	yes (with support)	yes (when distance between walls allows to remove support powder)	yes (with support made of the water-soluble material SUP707)
Surface quality	low (surface texture visible with the naked eye)	average (powder grains feel by touch)	high (elements with low roughness)
Support structures	reaction soluble material	non-sintered powder	reaction and the water-soluble material
Materials multiplicity	mainly the ABS, PLA	mainly the PA	7 basic materials and ca. 100 digital materials
3D printer cost	low (5-30 thousand euro)	high (over 100 thousand euro)	average (18-100 thousand euro)
Build material cost	average (50-270 euro/1 kg)	low (70 euro/1 kg)	high (200 euro/1kg; support 110 euro/1kg)
Post processing equipment	support material removes by a washer	air compressor, vacuum cleaner, media tumbling device, new and used powder tanks, extractors	support material removes by a washer
Technology destination	prototypes, low-volume production	series production	prototypes, piece production

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PORÓWNANIE DOKŁADNOŚCI I ROZDZIELCZOŚCI DRUKOWANYCH ELEMENTÓW 3D W WYBRANYCH TECHNOLOGIACH DRUKU

Streszczenie

W niniejszym artykule przedstawiono fragment prac wykonanych w ramach projektu „Wykorzystanie metod druku 3D (rapid prototyping) w połączeniu z badaniami optycznymi do szybkiego optymalizowania przestrzennych modeli wykonanych w technologii przyrostowej”. Artykuł rozpoczyna się przeglądem trzech wybranych technologii drukowania 3D - Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Material Jetting (MJ), które w dalszej części zostały przetestowane pod kątem dokładności i rozdzielczości. Testy dokładności zostały przeprowadzone na płaskich próbkach referencyjnych obrazujących dodatkowo teksturę wydruku. Próbki te zeskanowano w celu zweryfikowania odchyłek wymiarowych. Rozdzielczość zweryfikowano na modelach wymiennika ciepła oraz głowicy elektrowni wiatrowej cechujących się skomplikowaną konstrukcją. Najwyższą dokładnością i zarazem rozdzielczością cechuje się technologia PolyJet wraz z próbkami wydrukowanymi na maszynie Objet Eden 260 VS z rozpuszczalnym w wodzie materiałem podporowym SUP 707.

Słowa kluczowe: drukowanie 3D, dokładność, rozdzielczość wydruków, skomplikowane kształty.