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Influence of the layer thickness in the Fused Deposition Modeling process on the dimensional and shape accuracy of the upper teeth model

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Abstract. The article is focused on research of the influence of the layer thickness in the Fused Deposition Modeling (FDM) additive manufacturing method on shape geometrical and dimensional accuracy of parts. The digital model of the object (upper teeths) was obtained by intraoral 3D scanner 3Shape TRIOS used in dentistry. Based on the 3D (Three Dimensional) scanned digital model, the manufacturing of the upper teeths was realized on the FDM 3D printer Zortrax M200. The parts were manufactured in three different layer thicknesses. The manufactured parts was digitized by optical 3D scanner GOM ATOS Triple Scan. The dimensional and shape accuracy of the parts was evaluated in the software GOM Inspect.

1 Introduction

According to Békés [1], parts may be produced by adding materials (additive manufacturing methods), moving materials (casting technology, forming technology) and removing materials (machining technology). Additive methods of parts production include so called Rapid Prototyping (RP) that produces components a layer by layer [2]. The layer thickness in the RP process significantly determines the printed part´s quality. Lower layer thickness typically results in a part being printed with smoother surfaces and also better quality [3]. All 3D printing parameters are critical. The most solved parameters in the other publications are: layer thickness, part orientation, internal structure and used material.

The aim of this article is to publish the results of the experiment *"Influence of the layer thickness in the process of FDM on dimensional and shape accuracy of the upper teeth"*. It is known, that in the process of injection molding and additive manufacturing of plastic materials, some plastic materials, especially ABS (Acrylonitrile - Butadiene - Styrene) are susceptible to shrinkage. The model used for the experiment was a human upper teeth, obtained by 3Shape TRIOS optical intraoral 3D scanner. In second phase, the upper teeth were manufactured and subsequently 3D digitized by optical 3D scanner GOM ATOS II

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Triple Scan. The final step was the comparison of the printed models with the reference CAD model [4, 5, 6, 2] in the GOM Inspect software [7, 8].

2 3D model of upper teeth used for the experiment

The model used in the experiment is focused on dentistry. In dentistry, models of this type are used for a design and manufacturing of invisible teeth braces. The digital model, which was used in the experiment was a model of upper teeth. This model was chosen due to its importance for planning purposes in invisible teeth braces industry, where it is very important to preserve the best dimensional and geometrical accuracy [9, 10].

Acording to the collaboration between Slovak University of Technology, Faculty of Materials Science and Technology and Comenius University, Faculty of Medicine, we made the experiment, which is based on production technologies, materials and it is also connected with medicine.

On the 3D scanned model, there were also some significant areas (asymmetrical volumes) and also was necessary to create a cube for alignment in a fixture for a 3D scanning. Due to the facts, the editing of the upper teeth model was necessary. For model editing, the software Autodesk PowerSHAPE 2017 was used (Fig. 1.a).

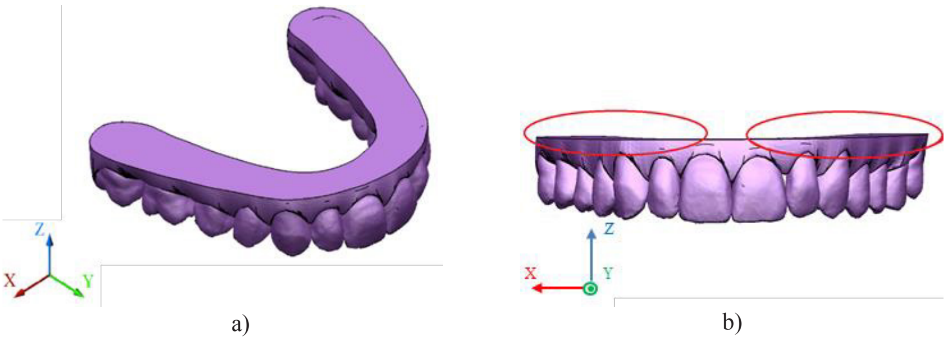

Fig. 1. Original STL model captured by intraoral 3D scanner 3Shape TRIOS: a) view ISO 3, b) view +Y (the asymmetrical areas are marked by ellipses).

2.1 Editing of the upper teeth digital model

At the beginning of editing, in the software Autodesk PowerSHAPE 2017, on the polygon mesh of the upper teeth, coordinate system was created. On the upper area of the upper teeth model, a surface was created (Fig. 2.a) due to separation for two single volumes. The asymmetrical areas divided by surfaces are shown on Fig. 2.b. This separation was made for creating of flat and symmetrical surface, which is situated on the bottom area of the teeth.

2.2 Creating of new elements on the upper teeth model

The surface used for dividing of models was created using the function *"Create primitive surface"*. After this step the function *"Split active solid"* was used for dividing of the two models. The upper volume was then removed and the original was closed and converted to the solid (Fig. 3.b) for a better alignment on 3D printer building platform. In the front of the upper teeth model, there was also created a cube (Fig 3.a), which was later used for alignment in a fixture for a 3D scanning.

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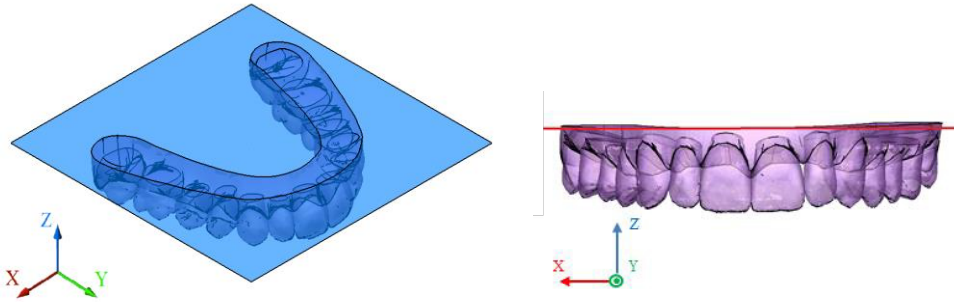
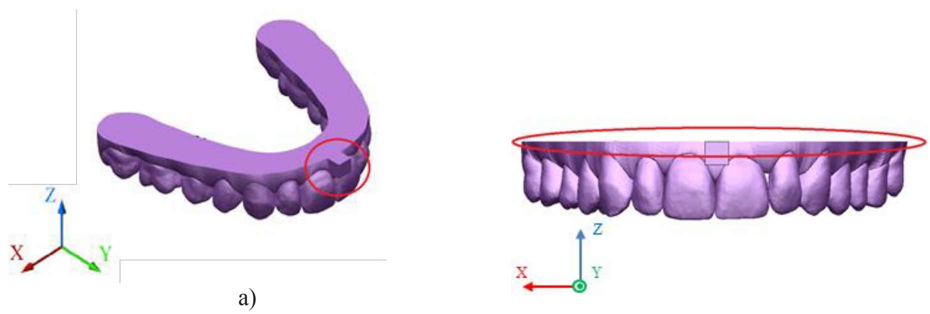


a) b)

Fig. 2. Editing of the upper teeth model in software Autodesk PowerSHAPE 2017:
a) surface created in the Z axis, b) asymmetrical areas divided by surface.



a)

b)

Fig. 3. Upper teeth model used for manufacturing:
a) cube for alignment in the front of the model, b) final symmetrical surface.

3 Fused Deposition Modeling method

FDM is a method of additive manufacturing in which a part is produced using layer by layer deposition of material. It is an important technology as it has potential to reduce the manufacturing lead time of the product. A lot of steps of FDM process are automatic. For example, layer thickness is selected manually among few options shown by the software. Layer thickness in FDM process has significant effect on many key characteristics which have influence on final quality and cost of the product [11, 12].

In the FDM technology, the used material is in a plastic wire form of diameter 1.75 or 2.85 mm, unwound from a coil. This fiber material is fed to the liquefier head where it is heated, fused and extruded through the nozzle in the form of fine fiber. There are several kinds of kinematic structures used in FDM. The movements of the liquefier head and 3D printer can be divided into three most used groups:

- head is moved in axis X, Y, Z,
- head is moved in axis X, Y and build platform is moved in Z axis.
- head is moved in axis X, Z and build platform is moved in Y axis [13].

The scheme of the FDM method (head is moved in axis X, Y and build platform is moved in Z axis) is shown in Fig. 4.

The fiber material used in the experiment was ABS with a diameter of 1.75 mm. ABS material was used in the experiment due to his minimal use in the production of the teeth models in dental applications for production of invisible teeth bracers.

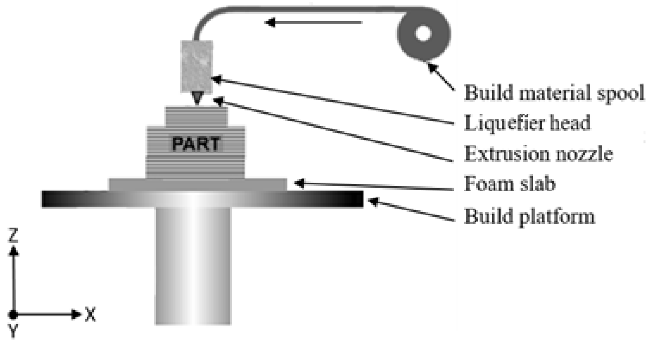


Fig. 4. Scheme of Fused Deposition Modeling [13].

ABS is an engineering plastic common used in FDM technology, that has butadiene part uniformly distributed over the acrylonitrile-styrene matrix. It possesses excellent toughness, good dimensional stability, easy processing ability, chemical resistance and cheapness. It is a low cost engineering plastic that is easy to machine [14, 15, 16]. ABS is an ideal material for structural applications when impact of resistance, strength and stiffness are required. It is widely used in FDM methods since it has excellent mechanical properties and is easy to paint and glue [17].

Parameters, which have influence on the dimensional and shape accuracy in the process of FDM are the following.

- infill,
- layer thickness,
- model orientation,
- material,
- nozzle temperature.

Manufacturing of the upper teeth was performed by FDM 3D printer Zortrax M200.

4 Layer thickness setting of the upper teeth digital model

For other additive manufacturing methods as Selective Laser Sintering (SLS), Selective Laser Melting (SLM) [18, 19, 20, 21], Poly-Jet Modeling (PJM) or Stereolitography (SLA) selection of layer thickness is also critical as for Fused Deposition Modeling (FDM). Layer thickness in all additive manufacturing methods have impacts on the printing process (time and cost) and the visual and physical properties of a printed part. Often the difference between an identical part printed at 100 μm and 200 μm is very hard to distinguish (Fig. 6.) however the 100 μm part will take twice as long to print and cost more [3, 10].

Understanding the final application of a part is always important when selecting the layer thickness. If a part has sharp edges that are required for the functionality of the part or if a part fits into another part then a smaller layer height is ideal [3, 22].

Fifteen prints were made in total. Five prints were manufactured for each type of layer thickness. The layer thickness which is recognized as the height of the deposited slice from the FDM nozzle as shown in Fig. 5. The layer thickness parameter is used to examine the influence of building thicker or thinner layers on the outcome quality [23].

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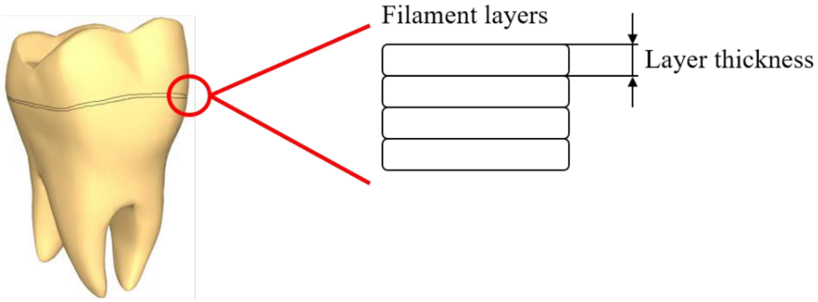

Fig. 5. Scheme of layer thickness in Fused Deposition Modeling process [22].

The layer thicknesses, which were used in the experiment:
- 0.09 mm,
- 0.19 mm,
- 0.29 mm.

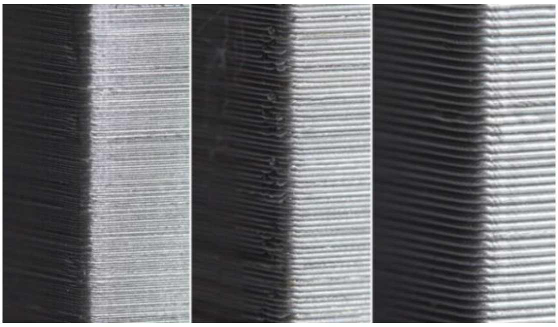

Fig. 6. A macro view of the FDM prints shown at the same scale for comparison: a) 0.09 mm, b) 0.19 mm, c) 0.29 mm [3].

5 Evaluation of the accuracy of shape and dimensions of the upper teeth

The printed models of upper teeth were digitized (Fig. 7.) using optical 3D scanner GOM ATOS II TripleScan. The measuring volume (MV), used for the digitization was MV 170 (170 x 130 x 130 mm). The resolution of the cameras was 5 Mpix (the measuring point distance was 0.07059 mm). The printed upper teeth models was matte coated [24].

Process of the 3D scanning is shown on Fig. 7. The comparison of each scanned model with the reference CAD model and evaluation of the dimensions was made in the software GOM Inspect V8 SR1. Parameters, which were measured are the distances between two points in the 5 single sections in total, from tooths marked as *Second molars (17 – 27)* up to tooths marked as *Canines (13 – 23)* (Fig. 8.). In the GOM Inspect software, the distance between points was measured by the function *"Construct – Distance – 2-Point Distance"*. These points were created by the function *"Fitting Point"*. All fitting points were created by the Chebyshev principle [25]. The scheme of the measured distances between point pairs is on the Fig. 9. and Fig. 10.

The shape deviation of the upper teeth model is visualised by the colour deviation map, which is created by the comparison of the reference CAD model and the 3D digitized parts.

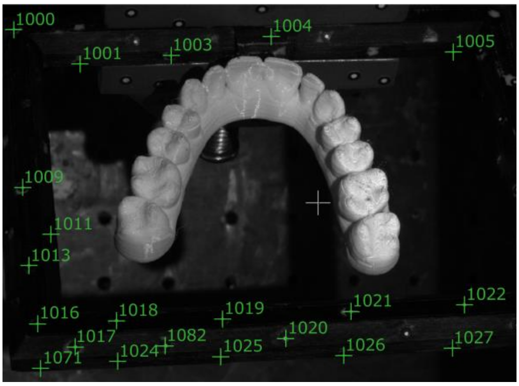

Fig. 7. Printed upper teeth model in the process of 3D digitization with recorded reference points.

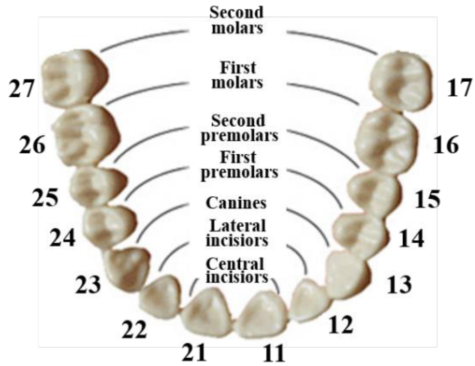

Fig. 8. Tooth marking (upper teeth) [9].

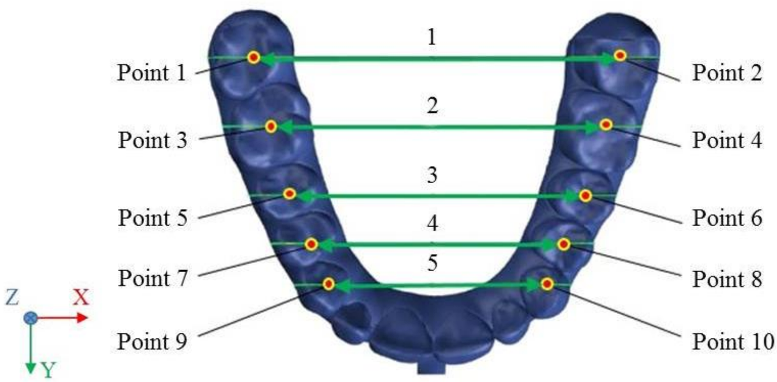

Fig. 9. The distance between point pairs in sections [7].

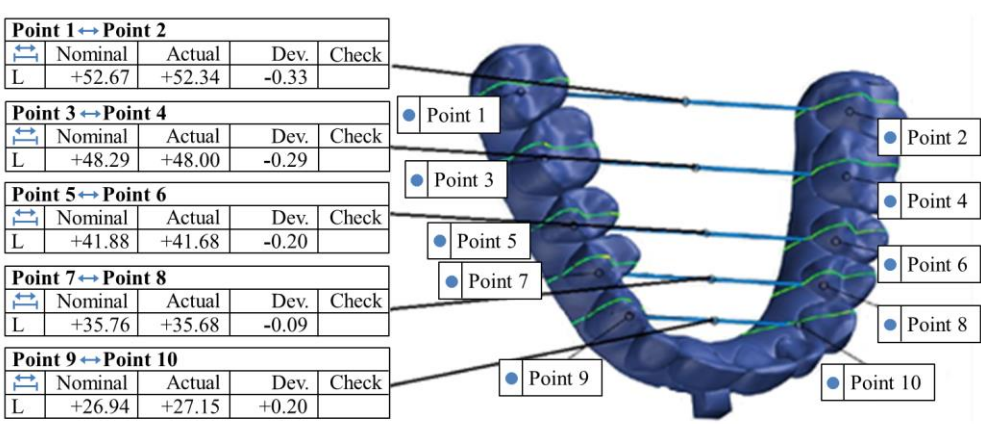

Fig. 10. The distance between two points on the upper teeth (layer thickness: 0.29 mm, print 4) [7].

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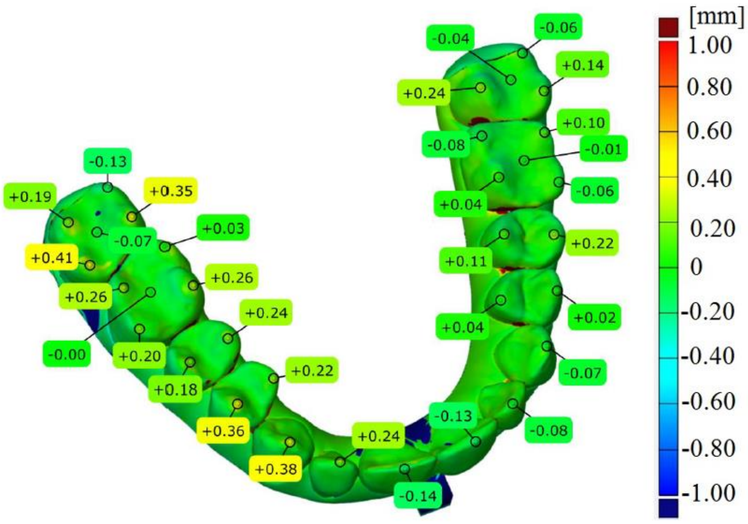

Fig. 11. Colour deviation map of the upper teeth model (layer thickness 0.09 mm) [7].

Table 1. Nominal distances, actual distances, deviations and arithmetic means of deviations [7].

Layer thickness: 0.09 mm							
Sections (points)	Nominal distances [mm]	Deviations [mm]					Arithmetical means [mm]
		Print 1	Print 2	Print 3	Print 4	Print 5	
1 (1 – 2)	+52.67	-0.27	-0.23	-0.21	-0.26	-0.27	**- 0.25**
2 (3 – 4)	+48.29	-0.25	-0.24	-0.19	-0.23	-0.24	**- 0.23**
3 (5 – 6)	+41.88	-0.19	-0.18	-0.16	-0.14	-0.20	**- 0.17**
4 (7 – 8)	+35.76	-0.10	-0.09	-0.11	-0.07	-0.14	**- 0.10**
5 (9 – 10)	+26.94	-0.02	+0.04	+0.04	+0.06	-0.01	**+ 0.02**

Table 2. Nominal distances, actual distances, deviations and arithmetic means of deviations [7].

Layer thickness: 0.19 mm							
Sections (points)	Nominal distances [mm]	Deviations [mm]					Arithmetical means [mm]
		Print 1	Print 2	Print 3	Print 4	Print 5	
1 (1 – 2)	+52.67	-0.30	-0.31	-0.33	-0.30	-0.34	**- 0.31**
2 (3 – 4)	+48.29	-0.25	-0.28	-0.30	-0.25	-0.25	**- 0.27**
3 (5 – 6)	+41.88	-0.24	-0.22	-0.21	-0.20	-0.23	**- 0.22**
4 (7 – 8)	+35.76	-0.11	-0.12	-0.14	-0.11	-0.09	**- 0.11**
5 (9 – 10)	+26.94	+0.11	+0.08	+0.10	+0.13	+0.09	**+ 0.11**

Table 3. Nominal distances, actual distances, deviations and arithmetic means of deviations [7].

Layer thickness: 0.29 mm							
Sections (points)	Nominal distances [mm]	Deviations [mm]					Arithmetical means [mm]
		Print 1	Print 2	Print 3	Print 4	Print 5	
1 (1 – 2)	+52.67	-0.30	-0.33	-0.38	-0.33	-0.44	**- 0.36**
2 (3 – 4)	+48.29	-0.27	-0.31	-0.29	-0.29	-0.29	**- 0.29**
3 (5 – 6)	+41.88	-0.19	-0.18	-0.22	-0.20	-0.25	**- 0.21**
4 (7 – 8)	+35.76	-0.07	-0.05	-0.12	-0.09	-0.11	**- 0.09**
5 (9 – 10)	+26.94	+0.21	+0.23	+0.16	+0.20	+0.18	**+ 0.19**

6 Conclusion

According to Table 1, 2 and 3 the most suitable layer thickness from the aspect of dimensional deviations was found to be layer thickness 0.09 mm with the smallest deviation. In the case of dimensional deviations, the most suitable layer thickness, with respect to the dimensional accuracy was found to be layer thickness with the smallest arithmetical mean deviation of -0.25 mm.

The second lowest dimensional deviations were found in layer thickness 0.19 mm with the arithmetical mean of deviation -0.31 mm.

The worst layer thickness in terms of dimensional accuracy was 0.29 mm, which created the greatest inaccuracies and distortions from required arithmetical mean of dimension -0.36 mm on the model of the upper teeth.

It was found that the layer thickness has a significant influence on dimensional and geometrical accuracy. The lowest shrinkage effect was found on the parts, where the amount of the single layers was the highest. In other words, the biggest shrinkage effect was found on parts where the amount of single layers was the lowest. Research of the layer thickness in the process of manufacturing by FDM method of upper teeth model was important due to the accuracy of the invisible teeth bracers. From the previous research is known, that layer thickness have a critical influence on the dimensional and shape accuracy.

Printed teeth models with the accuracy lower than ±0.25 mm are suitable as a model for the manufacturing of invisible teeth bracers. In the next step, the invisible teeth bracers are fabricated from thin transparent plastic plates using the vacuum press machine. The parameter *"layer thickness"* was chosen due to importance of the time build. Result from this research can be used in the optimal settings of *"layer thickness"* parameter in the process of manufacturing of teeth models with the assistance of FDM method.

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