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Examination of Layer Thicknesses of a Model Produced by Fused Filament Extrusion

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Abstract

Nowadays additive manufacturing continues to gain more and more space in industrial technology. In particular, FDM (fused deposition modelling) machines have become easily available to the public. Quality of parts is impacted by several factors. In this study we investigate layer thicknesses of a prototype manufactured from PLA, and we pay special attention to the thickness of sequentially deposited layers.

Keywords*: additive manufacturing, material extrusion, 3D printing, fused deposition modeling.*

1. Introduction

Nowadays additive manufacturing (AM) technologies are continuously being developed and drawn in industrial manufacturing. Applications in almost all fields is possible thanks to the versatility of AM technologies. It is a challenge for AM to prove its ability to produce real, competitive and robust products [1].

Amongst extrusion processes, fused deposition method (FDM) or (fused filament fabrication (FFF) is increasingly wide spread. These methods used not only form plastics [2, 3], but successful experiments have been performed for bulk metal glasses [4] and filaments containing ceramics [5].

Ensuring size and shape accuracy is an important prerequisite of competitiveness [6]. It is possible to reach good dimensional accuracies if extrusion is performed with constant temperature and mass flow controlled according to the curvature of the pathway of the printing head [7].

Frequently studied parameters in the properties of models produced by additive manufacturing are the following: layer thickness, extrusion temperature, raster angle, speed of printing head and orientation of the model within the tray. It can be demonstrated that layer thickness significantly influences tensile strength, flexural modulus and impact energy [8, 9].

Processing parameters with layer thickness amongst them plays important role also in simulation models devised for additive manufacturing [10].

Publications point out that layer thickness affects numerous mechanical properties of models additively manufactured with PLA (polylactic acid) material [11, 12].

It is an important and interesting tendency that several AM technology have become increasingly available for the wider public. Here we feature FDM (fused deposition modelling) technology amongst those.

FDM manufacturing machines are widely available on the market. They can be purchased even by private individuals. Production parameters they set up can be not optimal and because the microstructure of additive manufactured materials is sensitive to production parameters, we cannot know too much about the structure and material properties of parts produced by them. In this study we will especially focus on the spatial arrangement and thickness of layers.

2. Preparation of the test specimen

Electron microscopic study on the broken surface of a test specimen for Charpy impact test is a simple and effective way of investigating the layer thickness of bodies made of plastic [6].

Standard test specimens were manufactured by commercial Creality Cr-10 type, FDM 3D printer (**Figure** 1.). The dimensions of the test specimen were 80×10×4 mm. On one side of test specimen in the middle, there was a notch prescribed by the standard. The notch had an angle of 45 degrees, and a fillet radius of 0.25 mm. This notch was not created subsequently by material removing classical technology, such as cutting, or cold pressing. This notch was involved in the CAD model loaded in the additive manufacturing machine and was manufactured simultaneously with the whole part of the specimen.

The main dimensions of this manufacturing machine are 615×600×490 mm, and the size of the working area is 300×300×400 mm. Nozzle diameter is 0,4 mm, although other nozzles can also be applied with diameters of 0.3 and 0.2 mm. Layer thickness can be varied from 0.05 mm to 0.4 mm with steps of 0.05 mm. Size accuracy is ±0.1 mm. Highest printing temperature is 250 °C. The tray is heatable, and can be set to horizontal manually.

This manufacturing machine can use several different plastic filaments like PLA (poly lactic acid), ABS (acrylic butyl styrene), TPU (thermoplastic PUR elastomer).

Our 3 pieces of specimen were made of PLA (dark blue) at 205 °C nozzle and 70 °C build plate temperatures, with 0.1 mm layer thickness, printing speed 30 mm/s, and 100 % infill density.

Body models of the specimen were exported to STL (standard triangulation language) format.

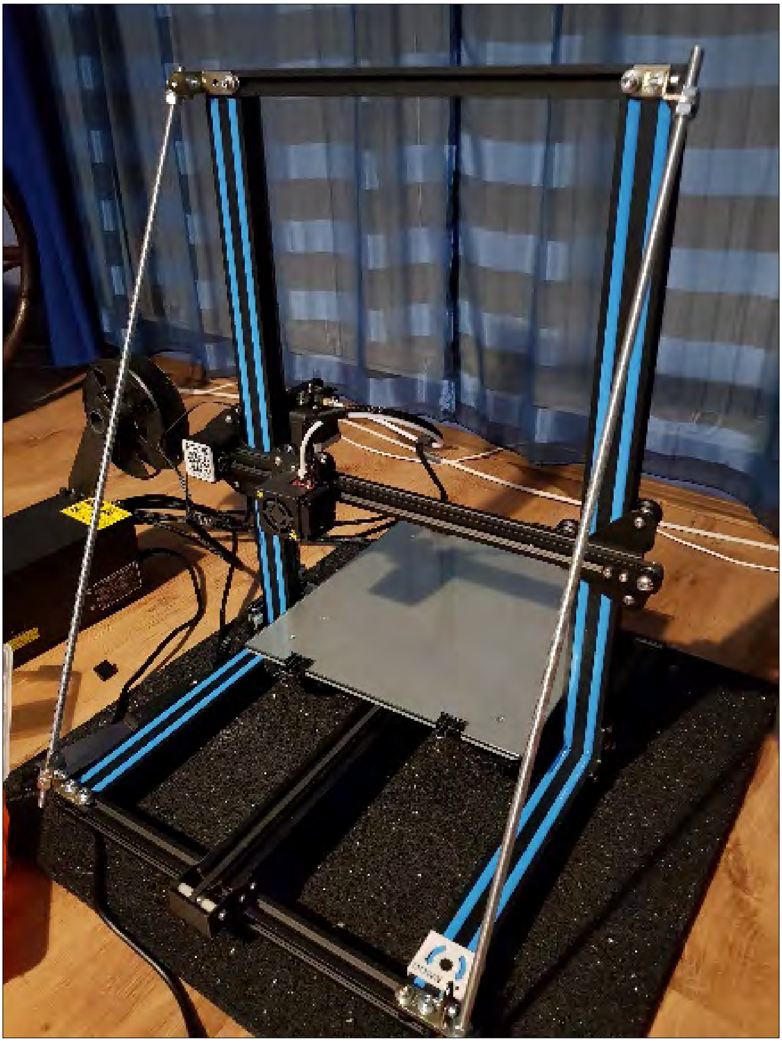

Figure 1. *Machine applied for manufacturing the specimen, Creality Cr 10*

Then those were processed by „Cura” free software, which these days is applied frequently worldwide for such purposes [3]. This software divides the body model into layers, and provides an environment for defining production and geometric parameters. Cura produces the gcode file which is applicable for control of the 3D printer.

Arrangement of strands within the specimen (raster) was 45 degrees angled. This can be observed in Figures 3. and 6.

3. Electron microscopic investigations

3.1. The electron microscope

A HITACHI SU-1050 scanning electron microscope is available at electron microscope laboratory at University of Nyíregyháza. Its maximal acceleration voltage is 15 kV, magnification ranges between 10 and 10000. The size of the tray is 150 mm.

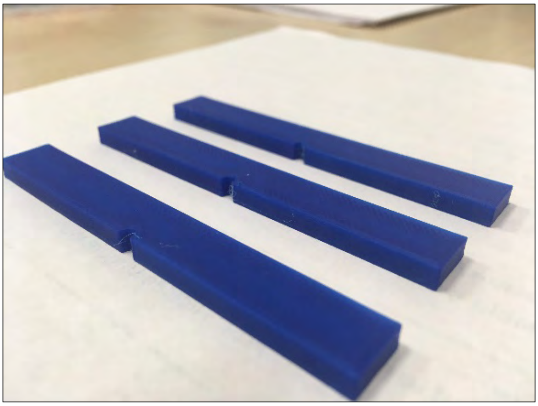

Figure 2. *The printed test specimens*

The sample is fixed with a carbonized tape, which can conduct electricity thereby eliminating static charge. Furthermore, the surface of sample is covered with a very thin layer of gold, which also serves to dissipate the charge coming from the electron beam. This is highly important for gaining a clear picture.

3.2. Sample preparation

After performing a Charpy impact test, the end part of the specimen containing the broken surface was cut. This was necessary to implement it onto the tray of the electron microscope. Its surface was coated with gold in order to avoid static electronic charging and to ensure good quality imaging. Then the sample was fixed onto the tray.

Figure 3. shows an overview of the sample fixed on the tray of the electron microscope. The lower part on the right side of the picture shows the surface of the notch, so this part is not generated by fracture, this is original as was manufactured. The left part of the figure shows the broken surface.

A magnified view of the portion of the picture included in the rectangle is shown in Figures 4. and 5. On these pictures the structure of original and broken surfaces can be easily observed. On the original surface, layers bulge and are squeezed. This is why the original surface of the model cannot be used for layer thickness measurements. On the broken surface, layers are well dissevered and are not deformed, therefore such surfaces are used for investigation of layer thickness.

Broken surface shown in Figure 6. can be divided to two parts. The surface of one is smoother, and the surface of the other is more proportioned.

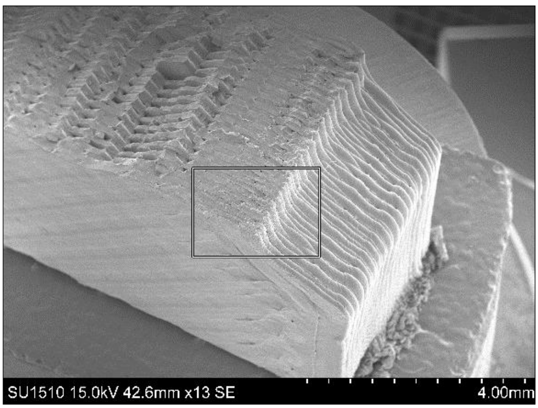

Figure 3. *An overview of the broken surface of the specimen*

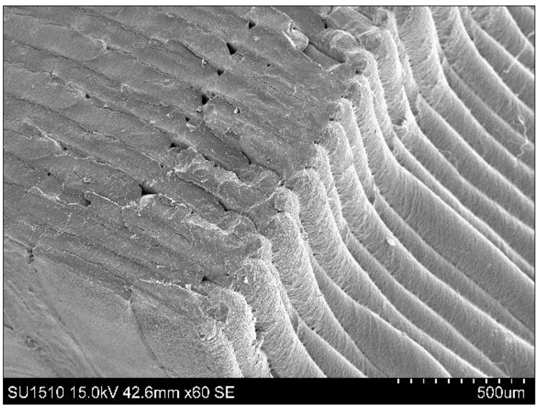

Figure 4. *Detail marked by rectangle on Figure 3. with magnification 8*

Different surfaces indicate slight differences in fracture process in the two region of the broken surface. Here we do not study this because our method is not suited to doing this. In general it can be stated that a smoother surface signifies brittle fracture and the jagged one, a ductile fracture. Delamination between printed layers cannot be observed.

The circled part in **Figure 6.** shows a crack, which is perpendicular to the direction of strands.

It can be noted that the structure of the proportioned, jagged surface resembles strain arrangement applied during the additive manufacturing process.

That part of the surface is more amenable to measurement, which is more is more proportioned, because borders of layers can be distinguished more effectively.

3.3. Investigation of layer thickness

Nominal layer thickness during the manufacturing was 0.1 mm, and the thickness of the specimen was 4 mm, so it was built up of 40 layers.

Figure 5. shows a portion of the broken surface, where 8 layers can be observed. Layers built up with different filament orientation can be well distinguished. This provides an excellent opportunity for measurement of layer thickness.

We selected such details on the broken surface in which the borders of layers could be easily observed. This is an indispensable condition of data recording by optical information. **Figure 7.** shows those parts of the broken surface that have been pointed out for this purpose.

It can be found out before measurement by survey that layers are not equal in thickness, and,

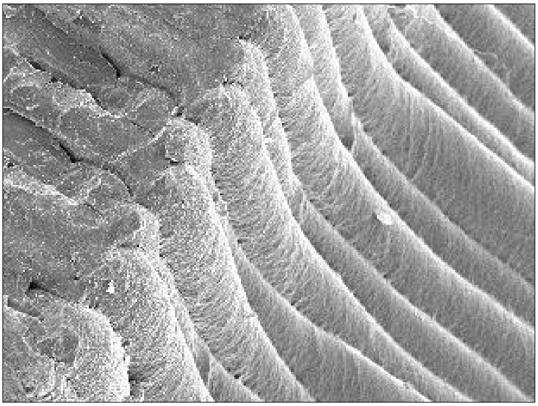

Figure 5. *Laminated structure observable on the surface of the specimen that is not suitable for measurement because of layers crinkled each order and deformed*

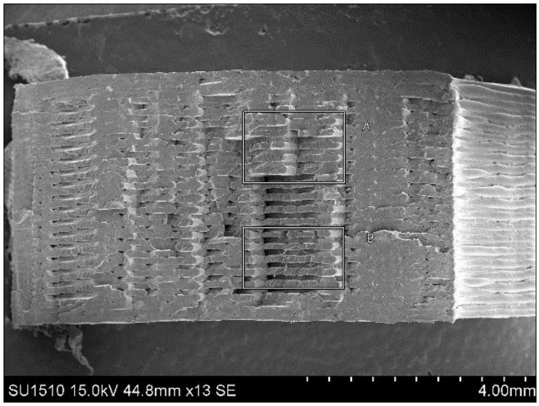

Figure 7. *Two details of the broken surface used for measurement of layer thickness (A and B)*

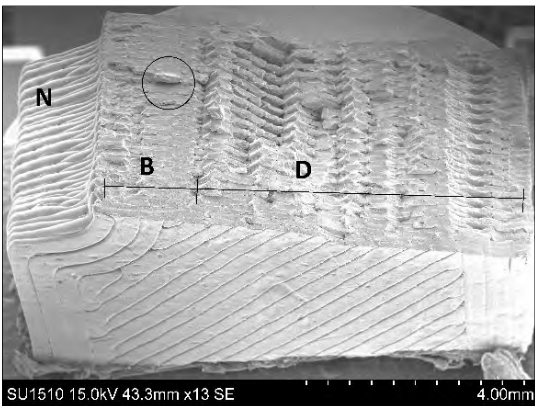

Figure 6. *Typical parts of the broken surface. N: original surface of the notch. B: area showing a bit more brittle fracture. D: area showing a bit more ductile fracture*

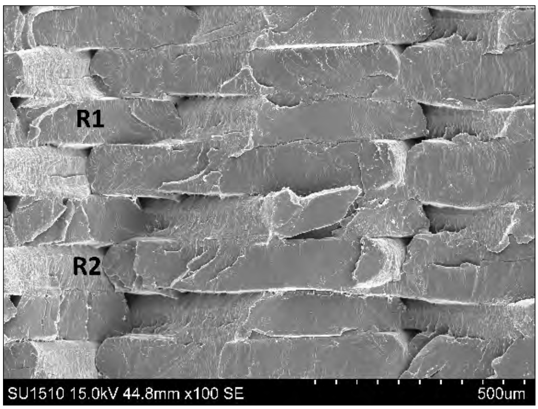

Figure 8. *A part of the broken surface that was used for layer thickness measurement (A)*

additionally, thickness can vary within a layer. That's why measurements were performed on multiple layers.

Three layers were selected in which cross sections of broken strands were visible. Five equidistant measuring points were determined for investigation. For reading of the thickness we applied the post processing software module of electron microscope, which provided distance of selected points by the operator in micrometer units.

Another detail was also selected on the broken surface where an additional two layers were studied in the way described above. This part of the surface is shown in **Figure 9.** We read thickness data. Data records are presented in **Table 1.**

It can be concluded from data presented in **Table 1.** and **2.** that the mean value of layer thickness in each case is larger than 0.1 mm, which was set as a production parameter. Standard deviation of data within a layer is high. In 4 layers of 5 investigated, more than 10 % difference can be observed between the highest and lowest data. Only for the seventh layer of the first investigated area (**Table 1.** 3rd row) can it be stated that layer thickness does not differ significantly from 0.1 mm, because of the large standard deviation.

The mean of layer thickness values is 114,4 µm, standard deviation of mean values

It can be determined by a statistical test that the mean of layer thicknesses differs from nominal value significantly. We assume that probability density function of layer thickness is a normal density function, and variance is approximated by standard deviation presented in the last column of **Table 1.** We apply a Z-test. Test statistics of Z are summarized in **Table 2.**

In the first four cases layer thicknesses significantly differ from nominal value even in the case of confidence level 0.005. In fifth row a significant difference cannot be proved.

The standard deviation of recorded data within a layer is high. Mean of means of layer thicknesses is 114.4 µm, standard deviation of means is 7.71 µm.

Table 1. *Measurement readings regarding layer thickness shown on Figure 7. in micrometer units*

	a (µm)	b (µm)	c (µm)	d (µm)	e (µm)	Average (µm)	Deviation (µm)
R1	117	113	121	124	106	116	7,05
R2	119	129	130	119	126	125	5,32
R3	128	116	128	118	122	122	5,55
R4	108	106	100	116	105	107	5,83
R5	97,2	91,3	116	120	94,2	104	13,26

Table 2. *Test statistics Z of data in Table 1*

Layer	u (value of Z-test)
R1	5.07
R2	10.51
R3	8.86
R4	2.68
R5	0.67

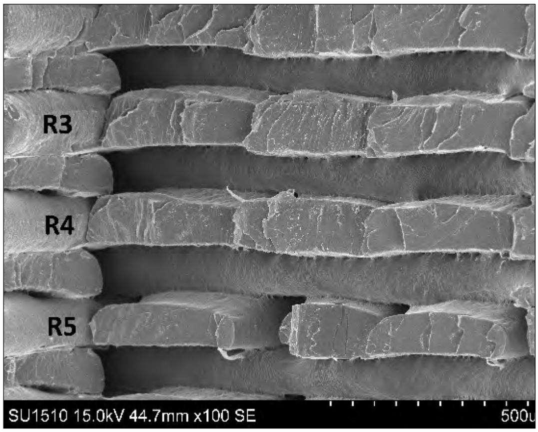

Figure 9. *Other part of the broken surface used for layer thickness measurement (B)*

4. Conclusions

The broken surface of the specimen has a jagged surface. This structure comes from the special arrangement of strands in the FDM manufactured bodies, and in itself cannot be used to diagnose a brittle or ductile nature of fracture.

On cross sections of fibres within a layer both flat and jagged fracture can be observed.

Layer thickness definitely changes from point to point, and significantly larger than 0.1 mm which was the prescribed parameter of the production.

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