

# Roughness and compressive strength of FDM 3D printed specimens affected by acetone vapour treatment

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**Abstract.** Rapid Prototyping technologies are the fastest growing technologies in the manufacturing of components and parts. There are many techniques which can be used with different materials and different purposes of produced part. Gradually, Rapid Prototyping systems have grown into Additive Manufacturing, because technology expansion brings faster production, improved manufactured components, and expanded palette of used materials. So now this techniques are also used for regular production of special parts, where is usual change of part design, where is necessary to produce variety of different designs and shapes. The following article deals with Fused Deposition Modelling (FDM) technology, the core of which is the manufacture models and components from thermoplastic polymers by deposition single fibres of semi-molten plastic material layer by layer. The article focuses on the results of research for testing of manufactured specimens by FDM technology. Components are modified by acetone vapour for surface smoothing. The purpose is to point out how the additional specimen treatment influence the strength properties. Presented paper shows realized experiments and measurements of compressive force on specimens and surface roughness which are influenced by acetone vapour treatment.

## 1. Introduction

This paper deals with one of Additive manufacturing technologies – Fused Deposition Modeling (FDM) also known as fused filament fabrication (FFF), which is focused on producing of parts and models from thermoplastic materials, such as ABS, PLA, Nylon and others.

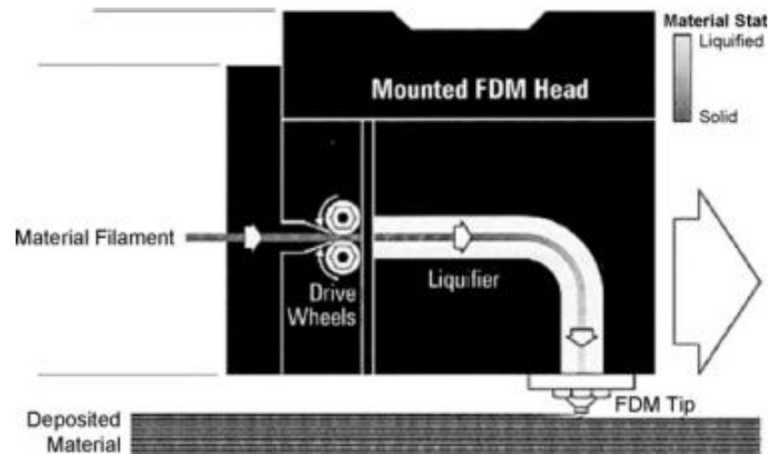
If we want to optimize production process, first of all we need to know how the system and the device behave with regards to different settings and with expectation of necessary properties of produced components. Following paper presents research on properties of produced specimens as model strength, which is necessary to predict the material properties of produced parts. The paper especially deals with compressive strength and roughness properties of FDM 3D printed specimens. There are also published papers which deal with similar problem and research how the chemical vapor affects the surface roughness of 3D printed parts and what are the mechanical properties of exposed parts [1, 2, 3]. But the difference is between the methodology how the vapor smoothing is in the process, what time and what tools are used.

For purpose of this paper we had to produce specimens for strength measurement. There have been used of FDM device that utilizes thermoplastic material for components production.

Fused Deposition Modeling (FDM) usually uses two types of materials – one for modeling and one for support. First, the model material is used to build the model. Second, the support material is used to build a support structure on the areas where the modeling material will overhang the rest of model [4].



This technique works on a principle similar to a fuse-gun [5]. The material is unspooled from the spool to the fuse-head, where it is melted and deposited on the working table (figure 1). After the completion of the model, the support materials are either broken away or dissolved in a special bath.



**Figure 1.** Scheme of FDM process [7]

The rapid prototyping use many different techniques which could be used with many different materials. Basically there can be used for different types of plastic materials, resins, and plaster. If we need the parts for final use from metallic materials, we can use different metallic materials for part production. Of course, the final properties such as parts are different, depending on chosen material, selected technology and also machine settings.

The standard materials used for plastic part modeling are ABS (Acrylonitrile Butadiene Styrene), PC (Polycarbonate), PLA (Polylactid acid), ASA (Acrylonitrile Styrene Acrylate), PETG (Polyethylene terephthalate), Nylon, HIPS (High Impact Polystyrene) or some special composite materials, for example Laywood, a composite of polymer and wood particles. All of these materials have some advantages and disadvantages. They have different processing requirements such as required temperature but also very important material properties as tensile strength, flexural strength or strength in compression. Selection of material for produced model depends mostly from available device type, because not all FDM devices are able to process all available materials. The other reason is how to choose the model material, when the device can process more types of materials that provide the final use of produced model and the material properties [6].

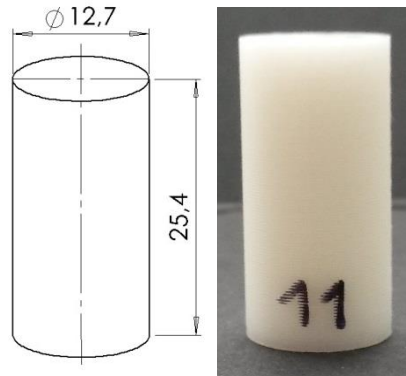
As is written above, it is necessary to take into consideration the ecological dimension. All mentioned plastic materials such as ABS, PC or Laywood are not environmental friendly. They practically do not decompose in the environment. But the PLA plastic material is environmentally friendly. This material is natural polymer, produced from corn, potatoes or sugar-beet. It is biodegradable, and in the environment will degrade and decompose in a few years in contrast to other polymers.

There are many of researches published in this field, which could be part of optimizing system, included in the database [7, 8, 9, 10]. All of these results are very important to proper setting of 3D printing device to reach the best result.

## 2. Experiment preparation

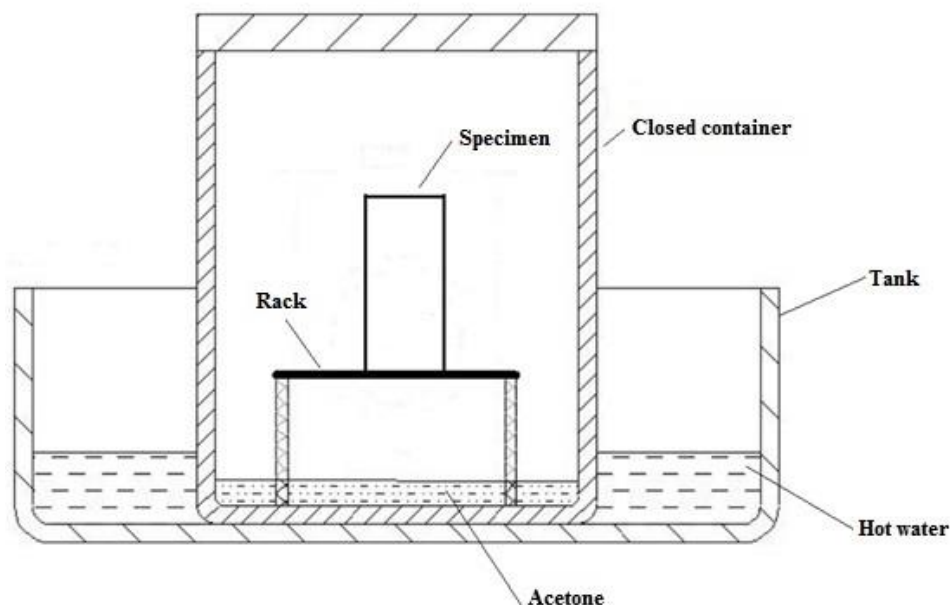
Presented research focuses on discovering strength properties of produced parts under compression load. The measurements are made of specimens from Dimension SST FDM device, produced from ABS plastic material. Printing process uses standard temperature from model material (ABS) 280°C, 3D printer chamber temperature 75°C, layer thickness 0,25mm. All specimens are produced from one spool

of material to ensure the same properties of raw material. The shape and dimension of specimens (figure 2.) are prepared in order of ASTM D695 standard, which determines conditions for plastic material testing within compression load. The diameter of cylindrical specimen is 12,7mm and the height is 25,4mm (2x12,7mm).



**Figure 2.** Scheme and picture of cylindrical specimen for compression testing of plastic materials

This research also focuses on specimens which are post-processed for surface smoothing with acetone for better surface design and roughness. This is realized by vapor smoothing. This method is done by placing specimens in a closed container with a small amount of acetone (100ml) in the bottom. This closed container is placed into a tank with hot water at 100°C. This is for heating to make acetone evaporate and cause specimen surface etching (figure 3.). Such surface will get fused and cause smoother surface.



**Figure 3.** Scheme for specimen preparation – vapor smoothing

Research also addresses how long the specimen is influenced by acetone vapor. The required output of this research is to specify the best time to reach the best surface quality without negative or with the best positive influence on specimen compressive strength.

### 3. Measurement

Measured and evaluated factors are compressive strength  $F_{max}$  (maximum compressive force when the specimen collapse) and surface roughness  $Ra$  (arithmetic average roughness). Because produced parts are usually mounted in different configurations, the condition of outer dimensions after surface smoothing are important. This research also accounts for this necessity and there are measured diameters of produced specimens.

#### 4.1. Compressive force measurement and evaluation

Mechanical press is used for the measurement of compressive force. Specimens are placed between fixed and moving parts of press. Recording device records all movements and applied forces during the testing period. The final maximum compressive force, when the specimen is broken, is recorded as illustrated in figure 5. When the specimen is pressing, the whole material volume is compressed and squeezed. After the critical compression the specimen could be usually deformed by two ways. Squeezed cylinder could break at the outer circumference (figure 4 – left) or could collapse and slide down to the side (figure 4 – right).

Loading in compressive testing is realized within a constant speed press of 10 mm.min<sup>-1</sup>. This speed is recommended by ASTM D695.



**Figure 4.** Two failure modes of deformation.  
Symmetrical deformation (left). Specimen collapsing to the side (right)

First measurement is made with clean specimens, which are not influenced by acetone. Measured values of maximum pressure force  $F_{max}$  for four repeating measurements for each specimen type are listed in table 1 and table 2. Average values from four repeated measured values are also in the tables. Difference  $\Delta$  (N) between “clean” specimen and others specimens which have been influenced by acetone within 5 minutes, 7,5 minutes and 10 minutes are observed to analyse how the maximum force changes compared to the maximum compressive force of the clear specimen. This difference is also displayed in percentage  $\Delta$  (%).

**Table 1.** Measured values of maximum compressive force.

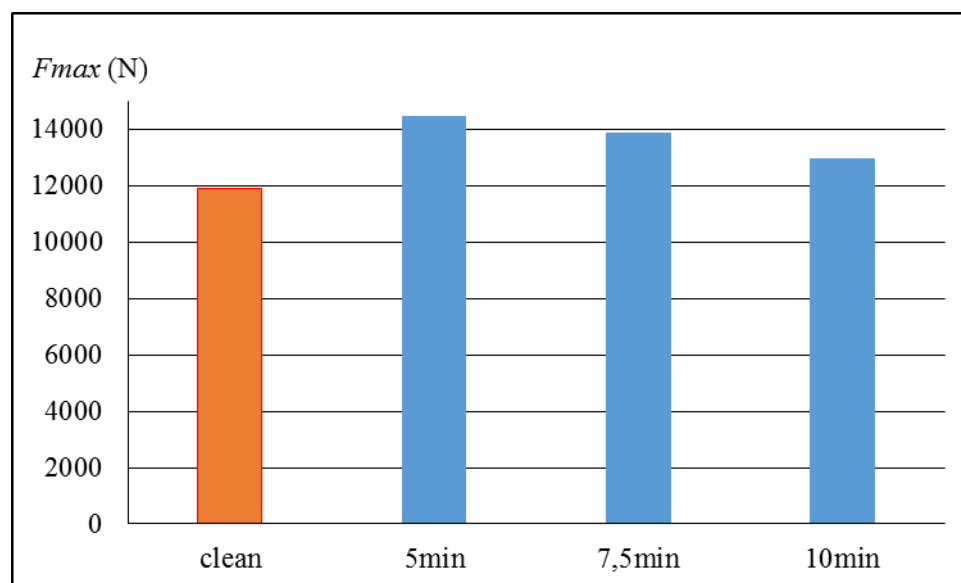
	$F_{max_1}$ (N)	$F_{max_2}$ (N)	$F_{max_3}$ (N)	$F_{max_4}$ (N)	$F_{max}$ (N)	$\Delta$ (N)	$\Delta$ (%)
Clean	11520	12010	12350	11825	<b>11926,25</b>		
5min	14000	14200	14950	14650	<b>14450</b>	2523,75	21,16
7,5min	14100	14050	13650	13720	<b>13880</b>	1953,75	16,38
10min	12240	13100	13300	13200	<b>12960</b>	1033,75	8,67

**Table 2.** Measured values of maximum compressive strength in MPa.

	$R_{max1}$ (MPa)	$R_{max2}$ (MPa)	$R_{max3}$ (MPa)	$R_{max4}$ (MPa)	<b><math>R_{max}</math></b> (MPa)	$\Delta$ (MPa)	$\Delta$ (%)
Clean	90,99	94,86	97,541	93,40	<b>94,19</b>		
5min	110,57	112,15	118,08	115,71	<b>114,13</b>	19,93	21,16
7,5min	111,36	110,97	107,81	108,36	<b>109,63</b>	15,43	16,38
10min	96,67	103,47	105,04	104,26	<b>102,36</b>	8,16	8,67

Measured values are also graphically illustrated on figure 5. The clear (not affected) specimen have the lowest value on compressive force compared to others specimens which are influenced by acetone. The best result is reached when the specimen is exposed to 5 minutes to acetone vapor. Mechanical properties of ABS plastic can be improved to about 21% higher level by this procedure.

On the other hand, higher exposure at 7,5 minutes and 10 minutes result in lower values. This is probably caused by higher volume of acetone affecting the ABS plastic material and probably degrade the internal structure of polymer strings. There could be deduced that if the time is too long, the ABS material will degrade and lose strength properties and will be useless. This assumption is based on different researches [11, 12].

**Figure 5.** Graphical illustration of measured values of maximum compressive force

#### 4.2. Roughness measurement and evaluation

Process of vapor processing of produced FDM parts have the primary purpose to smooth part surface. This has to be evaluated by measuring surface roughness to recognize what is the best time to reach the best part surface. The same specimens are used in this experiment; the roughness is measured before the specimens have been placed to the press for compression force measurement.

The change of surface is also visible by visual comparison (figure 6).



**Figure 6.** Presentation of different surface quality before (left) and after (right) vapor smoothing 5 min

The official measurement is realized by a special device assigned for this purpose – roughness tester Surtronic 3+. The device and measuring configuration are displayed in figure 7. This device can measure a wide spectrum of parameters, for example  $Ra$  - arithmetic average roughness,  $Rq$  - root-mean-square roughness,  $Rz$  - sum of maximum peak and maximum valley of a profile,  $Rmax$  - value of maximum peak of the profile and others.

Arithmetic average roughness  $Ra$  is the most common and most used in mechanical engineering, so it will be used as a comparing roughness parameter for this measurement. The specimen has to be fixed on the same table as the device to prevent any movements and distortions. The measurements have been made on different sides around the cylindrical specimen to eliminate accidental errors and irregular surface smoothing.



**Figure 7.** Measuring configuration for roughness measurement – roughness tester Surtronic 3+

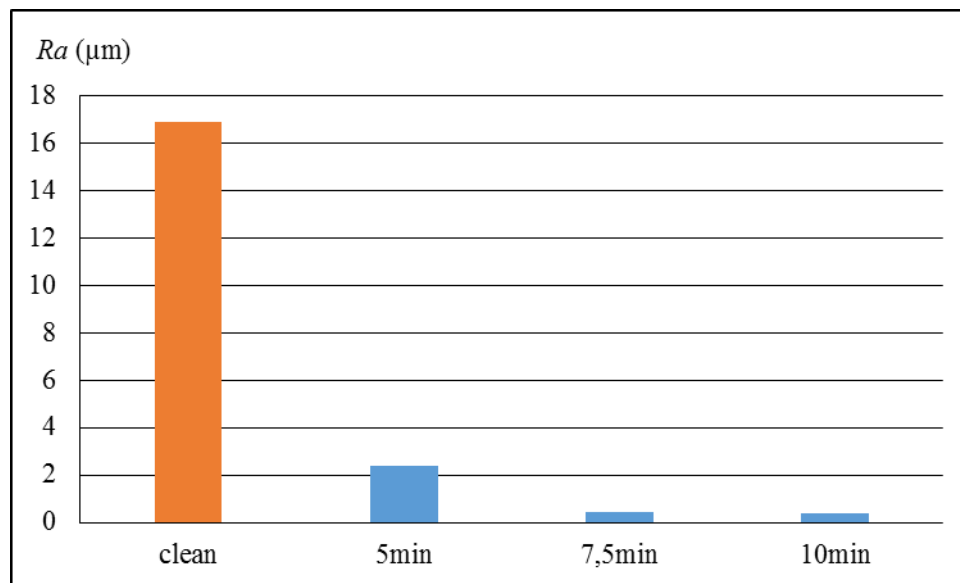
Measured values of Arithmetic average roughness  $Ra$  for five repeating measurements for each specimen type are placed in table 3. Average values from five repeated measured values are also in the table. Difference  $\Delta$  ( $\mu\text{m}$ ) between “clean” specimen and others specimens which have been influenced by acetone within 5 minutes, 7,5 minutes and 10 minutes are observed to see how the  $Ra$  changed compared to a clear specimen. This difference is also displayed in percentage  $\Delta$  (%), when the value  $Ra$  of clean specimen is set as 100%, and others values are deviations from 100%. For example in the case of specimen 5 minutes influenced by acetone, the value of 2,36  $\mu\text{m}$  is just 13,95% from the value measured on a clean specimen (16,92  $\mu\text{m}$ ).



**Table 3.** Measured values of Arithmetic average roughness  $R_a$ .

	$R_{a1}$ ( $\mu\text{m}$ )	$R_{a2}$ ( $\mu\text{m}$ )	$R_{a3}$ ( $\mu\text{m}$ )	$R_{a4}$ ( $\mu\text{m}$ )	$R_{a5}$ ( $\mu\text{m}$ )	<b><math>R_a</math> (<math>\mu\text{m}</math>)</b>	$\Delta$ ( $\mu\text{m}$ )	$\Delta$ (%)
Clean	16	17,8	16	17,2	17,6	<b>16,92</b>	-	100%
5min	2,2	2,8	3	1,8	2	<b>2,36</b>	-14,56	-86,05
7,5min	0,4	0,4	0,4	0,6	0,4	<b>0,44</b>	-16,48	-97,4
10min	0,6	0,4	0,2	0,4	0,4	<b>0,4</b>	-16,52	-97,64

Measured values are also graphically illustrated on figure 8. There is clear to see that clean (not affected) specimen have the highest roughness  $R_a$  compared to others specimens which are influenced by acetone. The best result and the best roughness is reached when the specimen is exposed to 10 minutes of acetone vapor. So it is possible to reach Arithmetic average roughness  $R_a=0,4 \mu\text{m}$ , which is only 2,36% from the initial value of 16,92  $\mu\text{m}$ . So we can get good and smooth surface by acetone vapor procedure. Almost the same roughness is also attained for a 7,5 min exposure. Relative change and jump are observed between a clean specimen and a 5 minute exposure. In the future it could be interesting to make experiments also with the time between 0 and 5 minutes to see how the surface is changing. More than 10 minutes is counterproductive because the etched surface or the top layers of cylindrical specimens are flowing down due to gravity.

**Figure 8.** Graphical illustration of measured values of Arithmetic average roughness  $R_a$

## 5. Conclusion

Presented paper shows that there is big influence of surface smoothing process for ABS parts produced on FDM device. Smoothing process rapidly influencing the compressive force and this process also reinforced the part and make it stronger compare to not influenced specimens. It is significant that the compressive strength of specimen can be increased by more than 21 percent when the part is exposed to 5 minutes of acetone vapor. On the other hand, if this time is longer, the strength of specimens is decreasing.

Smoothing process is made for primary depression of surface roughness. This process rapidly decreases roughness from Ra value of 16,92  $\mu\text{m}$  down to 0,4  $\mu\text{m}$  when the specimen is influenced by 10 minutes of acetone vapour without significant changes in the diameter of a cylindrical specimen.

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