The impact of temperature changing on surface roughness of FFF process

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Abstract. The current study investigates the surface roughness of models produced by a 3D printer. All models were produced by addition of solid material, a process called fused filament fabrication (FFF): initial extrusion into plastic filament, second extrusion and trace-binding during the 3D printing process. A low cost 3D printer Ultimaker was used to print these items. Polylactic acid (PLA) was used as main polymer material for printing. The temperature was parameter under direct variations in order to examine if there was an influence on roughness of 3d printed models. The surface roughness parameters were: the average mean surface roughness (Ra, μm), the surface roughness depth (Rz, μm), the total height of the roughness profile (Rt, μm) and the arithmetic mean width of profile elements (Rsm, μm). The examination showed conditionality: as temperature was increased the surface roughness parameters were further decreased.

1. Introduction
Fused filament fabrication (FFF), can also be found as fused deposition modeling (FDM) that creates computer aided design (CAD) models to be 3D printed from Polylactic Acid (PLA) [1], Acrylonitrile Butadiene Styrene (ABS) or similar substrates.

This process is very easy and cheaper than other methods of rapid prototyping thus can be implemented in many applications: Architecture, Product Design, Biomedicine, Aerospace, Education [2] etc.
The FFF 3D printers are very popular (appliance also in home 3D printing) during last years on the market. These machines deposit filament of a certain material (mainly thermoplastics) into thin layers which are cooled very fast (with cold fan) thus the next layer can be added into the previous layer in figure 1. Thermoplastic polymers are plastics which become semi-liquid above a specific temperature and return to a solid state when cooling down. The 3D model is made by positioning of the nozzle in relation to the Plexiglas print bed, while depositing fused PLA (or ABS) onto the built part [3]. All models were printed on this print bed. This Plexiglas bed may be stationary or may move along one the X, Y, Z axes. In this research a 3D printer with a stationary print bed was used. There are various printers with different technical specifications such as: quality of print (Layer resolution), build volume, print speed. The main difference of SLA (Stereolithography) 3D printers is that SLA printers are used for high detailed printed objects. One is able to decide which parameters can change to take the best print in FFF process [4]. In this research Cura software was chosen.

Cura (created by the makers of the Ultimaker printer) is a free software that prepares the model that is designed in the CAD program (Autocad in this case). This software converts STL (or OBJ) files (slice the model) into G-Code. The 3D printer must handle the file that is designed in order for the model to be translated into a suitable format.

Dividing the model into thin layers is called slicing. Cura is suitable software for Ultimaker printer for performing slicing. By this software lots of settings can be changed such as layer height or layer thickness. All CAM (Computer Aided Manufacturing) software need an STL file in order to turn a 3D model into a machine (3D printer) friendly format. This format is called G-Code and Cura converts STL files to G-Code.

2. 3D Printer
All 3D printers are composed of electromechanic components (hardware) and software applications that are developed by engineering companies [5]. Home edition 3D printers have easier functions than rapid prototyping machines. These are suitable for small offices (home 3D printing) and use less energy. Manufactured for printing small plastic objects, home edition 3D printing technology is a low cost procedure and there is continuous development so the price of these machines will be reduced compared to expensive rapid prototyping machines.

For measures in this research popular 3D printer called Ultimaker was used (figure 2). The Ultimaker Original (by Ultimaker Ltd) is an open source 3D printer and it is based on the Rep Rap (Replicating Rapid-prototyper) technique. This model has been awarded as the fastest and most accurate 3D printer in 2012. It can print complex drawings that have been designed in CAD software. Ultimaker supplies PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene) as materials for printing.
3. Technical details
Some technical specifications of the printer are given: Layer resolution up to 20 µm, Build volume 21 cm × 21 cm × 20.5 cm, Print speed 30-300 mm/s, Travel speed 30-350 mm/s, Recommended filament diameter 2.85 mm, Nozzle diameter 0.4 mm, Printing technology Fused filament fabrication (FFF), Stand-alone SD-card printing, Frame dimension X Y Z: 35.7 cm × 34.2 cm × 38.8 cm, Operation nozzle temperature: 180-260 °C, Software: Cura - Official Ultimaker. PLA is a biodegradable polyester and non-toxic material suitable for many applications [6]. There are many applications such as medical usage, injection molding, packaging and 3D printing within past years. Its smell is very pleasant during printing. With this material you can get very good quality of prints in any color.

PLA or Polylactic acid derived from renewable resources like corn starch, tapioca roots or sugarcane. It is a very ecological thermoplastic polyester because it naturally degrades in outdoor environment conditions. Different parameters in RepRap additive manufacturing system for PLA models could be selected [7].

For this research a 3D model was designed (figure 3) by Autocad software and it was extracted in STL format. It was converted by Cura software to G-Code and the layer was built with Ultimaker 3D printer. Suitable settings have been put into software changing only two parameters (filament temperature and shell thickness) each time. The printing settings were: layer thickness (height - mm) - 0.2, shell thickness (mm): 3-2-1, fill density (%) - 20, print speed (mm/sec) - 100, printing temperature (°C): 210-220-230.

Figure 3. 3D model
Figure 4. (a) 1st item (3 mm, 210 °C), (b) 2nd item (3 mm, 220 °C), (c) 3rd item (3 mm, 230 °C), (d) 4th item (2 mm, 210 °C), (e) 5th item (2 mm, 220 °C), (f) 6th item (2 mm, 230 °C), (g) 7th item (1 mm, 210 °C), (h) 8th item (1 mm, 220 °C), (i) 9th item (1 mm, 230 °C)

Nine items were printed (figure 4), shell thickness:
- D1 = 1 mm;
- D2 = 2 mm;
- D3 = 3 mm;

and three different temperature printing parameters were used:
- T1= 210 °C;
- T2= 220 °C;
- T3= 230 °C.

All models were measured on each surface roughness by a device, which is a user friendly instrument for surface roughness measurement Mitutoyo Surftest SJ-210, designed as a handheld tool. By this device surface roughness waveforms can be viewed on a color LCD screen as well.

The surface texture parameters measured during this examination were the following:
• **Ra (μm):** the arithmetic mean surface roughness (arithmetical mean of the sums of all profile values). Ra is by far the most commonly used parameter in surface finish measurement and for general quality control. Despite its inherent limitations, it is easy to measure and offers a good overall description of the height characteristics of a surface profile [8].

![Figure 5. Surface texture parameters](image)

\[
Ra = \frac{1}{\ell} \int_0^\ell f(x) \, dx
\]

**Figure 5. Surface texture parameters**

• **Rz (μm):** surface roughness depth. It is the arithmetic mean value of the single roughness depths of consecutive sampling lengths.

![Figure 6. Surface texture parameters](image)

\[
Rz = \frac{1}{5} \left( Y_{p1} + Y_{p2} + Y_{p3} + Y_{p4} + Y_{p5} \right) + \frac{1}{5} \left( Y_{v1} + Y_{v2} + Y_{v3} + Y_{v4} + Y_{v5} \right)
\]

*Y_{p1}, Y_{p2}, Y_{p3}, Y_{p4}, Y_{p5}*: Heights of the of top five peaks within the sampled portion of reference length \( \ell \)

*Y_{v1}, Y_{v2}, Y_{v3}, Y_{v4}, Y_{v5}*: Heights of the five lowest valleys within the sampled portion of reference length \( \ell \)

**Figure 6. Surface texture parameters**

• **Rt (μm):** total height of the roughness profile, i.e., the vertical distance between the highest peak and the lowest valley along the assessment length of the profile. This parameter is very sensitive to the high peaks or deep scratches.

![Figure 7. Surface texture parameters](image)

**Figure 7. Surface texture parameters**
- Rsm (μm): the arithmetic mean width of profile elements. It is the arithmetic mean value of the widths of the profile elements of the roughness profile, where a profile element is a peak and valley in the roughness profile.

![Rsm Diagram]

**Figure 8.** Surface texture parameters

The obtained results are in the following tables:

**Table 1.** Surface roughness measurements (1mm shell)

| R (mean) | Model 1 (T₁, D₁) | Model 2 (T₂, D₂) | Model 3 (T₃, D₃) |
|----------|------------------|------------------|------------------|
| Rₐ (μm) | 17.00            | 14.66            | 14.08            |
| Rz (μm) | 83.47            | 75.96            | 63.98            |
| Rt (μm) | 123.80           | 103.90           | 68.86            |
| Rₚₘ (μm) | 229.73           | 224.10           | 203.10           |

![Graph of surface roughness parameters]

**Models 1-3**

- 210 °C
- 220 °C
- 230 °C

**Surface roughness parameters**
### Table 2. Surface roughness measurements (2mm shell)

| R (mean) | Model 4 \((T_1, D_1)\) | Model 5 \((T_2, D_2)\) | Model 6 \((T_3, D_3)\) |
|----------|------------------------|------------------------|------------------------|
| \(R_a (\mu m)\) | 16.48 | 13.04 | 12.84 |
| \(R_z (\mu m)\) | 85.74 | 62.20 | 62.26 |
| \(R_t (\mu m)\) | 85.74 | 83.07 | 69.22 |
| \(R_{sm} (\mu m)\) | 321 | 205.46 | 196.73 |

### Table 3. Surface roughness measurements (3mm shell)

| R (mean) | Model 7 \((T_1, D_1)\) | Model 8 \((T_2, D_2)\) | Model 9 \((T_3, D_3)\) |
|----------|------------------------|------------------------|------------------------|
| \(R_a (\mu m)\) | 21.77 | 19.49 | 12.98 |
| \(R_z (\mu m)\) | 128.48 | 98.21 | 57.84 |
| \(R_t (\mu m)\) | 74.39 | 145.60 | 65.62 |
| \(R_{sm} (\mu m)\) | 204.3 | 248.50 | 198.5 |
4. Conclusion
The examination of the influence of the temperature factor to the surface roughness was made. The results showed that all surface roughness parameters $Ra$, $Rz$, $Rt$, $Rsm$ decreased (smoother surfaces when R parameters tend to zero) as the temperature increased from 210 °C to 230 °C.

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