Evaluation of dielectric properties of 3D printed objects based on printing resolution

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Abstract. Fused Deposition Modelling (FDM) is one of the most common methods of 3D printing used in many fields of industry, especially in development departments. Since plastics are fundamental materials for electronics industry, the aim of this work is to examine dielectric properties of objects printed from such materials. This work’s contribution is the evaluation of the dependency of the printed objects properties on printing quality and the use of 3D printed plastic components in electronics.

For the experiment, three commonly used materials in FDM were chosen – PLA, ABS and PET-G. The materials were pure without any additional admixtures and the relevant test samples were printed with different printing resolution (height of one layer). The following properties were examined – permittivity, dissipation factor and dielectric strength. The results showed that permittivity slightly decreased with increasing height of one layer. Dissipation factor varied significantly in the measured range and there was no apparent dependency on the printing resolution. Rather, it was an indicator of the printing quality. Dielectric strength also slightly decreased with the decreasing resolution; however this parameter was governed primarily by the employed material. Generally, an improvement of the dielectric properties of these materials is required due to a relatively small dielectric strength, for example by adding admixtures to the base material or better printing quality.

1 Introduction

Classic methods of manufacturing (mould pressing, cutting etc.) are time-consuming and expensive, so other methods are required for a quick prototyping. With an expansion of Additive Manufacturing (AM) and 3D printing technologies, the time of development of electronic devices rapidly decreased. [1]

Fused Deposition Modeling (FDM) is one of the methods of 3D printing that uses mainly thermoplastic materials. Its principle is simple and, in general, it can print any material that melts and then solidifies again. Obviously, there are requirements on its viscosity during liquid state to achieve good adhesion to the printing substrate and cohesion of layers. Standard FDM uses material in the form of a string supplied on a spool (filament). Commonly used materials are thermoplastic polymers like acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol-modified (PET-G), poly-lactic acid (PLA), polyamide (nylon), co-polyester (CPE), polycarbonate (PC) etc. [2]
These materials are dielectric and some of them find use in electronics industry as insulators, e.g. wire insulation, boxes and construction parts. Among the other materials’ electrical properties, dielectric strength presents a very important parameter that determines their viability in power electronics, where high voltages typically occur. Other relevant dielectric parameters are permittivity and dissipation factor. Both these factors determine the behavior of the material under electric field and the losses caused by alternating current flow.

FDM does not create ideally homogenous solid components; therefore there are differences in properties of final objects in comparison with standard methods of manufacturing, e.g. moulding. The differences are caused by air-gaps present within the 3D object (between lines in X and Y axis and layers in Z axis) or defective cohesion of lines and layers etc. Some of the influencing parameters are the printing resolution (height of one layer), Z axis offset and the temperature of the extrusion head. [3]

According to [4], objects printed by FDM from materials ABS and PLA have acceptable dielectric properties and dielectric strength for lower voltage level applications. The contribution of this study is to examine the mentioned dielectric properties of materials designated for FDM, respectively the properties of printed objects from these materials in dependency on printing quality. In this experiment, the quality is defined by the printing resolution.

The comparison of the measurement results with the known values of chosen parameters and the results from similar work [4] should lead to better understanding of how to use these materials and FDM in electronics industry, especially for low-frequency and power applications.

### 2 The experiment description

For the experiment, three commonly used materials mentioned above were chosen – ABS, PLA and PET-G. Filaments (1.75 mm) were delivered directly from the producers of 3D printer filaments; they should not contain any additional admixtures.

#### Table 1. Measured samples

| Sample identification | Amount | Material | Printing resolution (µm) | Printing temperature (°C) | Manufacturer of filament |
|-----------------------|--------|----------|--------------------------|--------------------------|-------------------------|
| PLA50                 | 10     | PLA      | 50                       | 220                      |                         |
| PLA100                | 10     | PLA      | 100                      | 220                      |                         |
| PLA150                | 10     | PLA      | 150                      | 220                      |                         |
| PLA200                | 10     | PLA      | 200                      | 220                      |                         |
| ABS50                 | 10     | ABS      | 50                       | 255                      | Prusa                   |
| ABS100                | 10     | ABS      | 100                      | 255                      | Polymers, Czech         |
| ABS150                | 10     | ABS      | 150                      | 255                      | Czech Republic          |
| ABS200                | 10     | ABS      | 200                      | 255                      |                         |
| PET50                 | 10     | PET-G    | 50                       | 235                      |                         |
| PET100                | 10     | PET-G    | 100                      | 235                      |                         |
| PET150                | 10     | PET-G    | 150                      | 235                      |                         |
| PET200                | 10     | PET-G    | 200                      | 235                      |                         |

The samples were designed as circles with a diameter of 5 cm and width of 0.6 mm. The width was chosen as the least common multiple of the four chosen widths of one layer – 50, 100, 150 and 200 µm. Altogether, ten samples of each combination (material and printing resolution) were prepared. The simplified sample identification can be seen in Table 1.

Prusa i3 MK3 that utilized the RepRap concept was chosen as the 3D printing device, as it represents one of the most common printers. [5] The digital model of the sample was converted to printer instructions by open-software Slic3r with the following settings for all materials – 100 %
filling density with fill angle 90°, one line of perimeter and default speed of printing recommended by printer producer. The printing temperatures were slightly changed from the recommended values according to the observation during the printing of the first few samples, as can be seen in notation in Table 1. The printer was carefully calibrated in Z axis to get the best possible results.

2.1 Permittivity and dissipation factor measurement

For low frequency and low permittivity measurements, the parallel plates method (or capacitor method) is optimal. [6] Therefore, a special electrode system was used. It consisted of two parallel circle electrodes with the same diameter as the sample and a spring system for fixation of the sample. The system was connected to LCR meter APPA 703 by 4-wires probe. After putting the sample between the electrodes, capacitance and dissipation factor were measured with measuring frequency 100 Hz, 1 kHz and 100 kHz. From capacitance, permittivity can be calculated as:

\[
\varepsilon_r = \frac{C \cdot w}{\varepsilon_0 \cdot (\pi \cdot d^2 / 4)}
\]

where \( C \) (F) is the measured value of the capacitance, \( w \) (m) is the width of the sample, \( \varepsilon_0 = 8.85 \cdot 10^{-12} \text{F.m}^{-1} \) is the permittivity of vacuum and \( d \) (m) is the diameter of the sample.

2.2 Dielectric strength measurement

The measurement of the dielectric strength was carried out on an electrode system connected to a 50-Hz AC voltage source. The system consisted of two cylindrical electrodes with a diameter of 6 mm, between which the samples were inserted. Afterwards, the source was connected to the upper electrode and the applied voltage was being increased linearly (2 kV/sec) until a breakdown occurred. The value of breakdown voltage of the sample was equal to the value of RMS voltage measured at the moment of breakdown. A calibrated voltmeter METEX M-3850 with a high voltage probe Agilent 34136A was used for voltage measurement. All of the experiments were realized inside a container filled with natural insulating oil. The oil had a similar permittivity as the samples, which helped to eliminate the possible surface discharges. The samples were immersed in the oil only during the test (~1 min), which prevented any significant oil ingress into the material.

3 Results

The results from the permittivity measurement are illustrated in the following figures. Figure 1 represents the dependence of permittivity of each material on the measuring frequency for printing resolution 150 µm. Such a resolution was chosen as it had the lowest failure occurrence during the printing. It is apparent that the value of permittivity slightly decreases with increasing frequency for all three examined materials. In Figure 2, the dependency of permittivity on printing resolution is depicted for measuring frequency 100 Hz. Except for ABS, the permittivity of the examined samples was larger for smaller height of one layer.
The results from dissipation factor measurement are shown in Figure 3 and Figure 4. No apparent dependency on printing resolution was found; nevertheless dissipation factor slightly decreased with frequency. The largest difference occurred between 100 Hz and 1 kHz for the PET50 samples; however, these samples also had the highest standard deviation. In general, high value of deviation was calculated for most of the dissipation factor measurements, therefore the data were not statistically credible.

The data of the permittivity measurement were statistically tested by Student’s t-test with significance level $\alpha = 5\%$; $p$ values for differences between the highest and lowest printing quality for permittivity measurement with the measuring frequency 100 Hz ($p_{DC}$) can be found in the summary in Table 2. For the dissipation factor measurement, $p$ values are not listed in the table.

The results of dielectric strength measurement can be seen in Figure 5, which represents the dependence of dielectric strength on the printing resolution. The two-parameter Weibull distribution was applied on the data (according to the standard IEC 62539:2007). This distribution is commonly used for describing a process of electric degradation, but in the case of the linearly increasing voltage with time, it is possible to interchange time axis with field strength axis. Scale ($\alpha$) and shape ($\beta$) parameters of the Weibull distribution can be seen in Table 2. The estimated scale parameter was regarded as the dielectric strength. In the case of dielectric breakdown tests, the value of the shape parameter should be much larger than 1 (at least 10), as that means the results are distributed in a narrow band around the mean value.

ABS had the highest value of dielectric strength, but it also showed no apparent differences between the resolutions. For PLA samples, the value of dielectric strength was lower in comparison...
with ABS and the dielectric strength had decreasing character with increasing resolution. For PET-G, the dielectric strength was significantly worse for higher printing resolutions.

**Table 2.** Results of dielectric parameters measurements for materials suitable for 3D printing (measuring frequency 100 Hz for permittivity and dissipation factor, 50 Hz for dielectric strength)

| Sample  | Average permittivity ($\varepsilon$) | Statistical significance ($p_{dc}$) | Average dissipation factor (-) | Weibull shape parameter ($\gamma$) | Dielectric strength (kV/mm) | Weibull scale parameter ($\beta$) |
|---------|-----------------------------------|----------------------------------|-------------------------------|---------------------------------|-----------------------------|---------------------------------|
| PLA50   | 2.36 ± 0.26                       |                                  | 0.013 ± 0.016                 | 34.1                            | 12.9                        |
| PLA100  | 2.10 ± 0.20                       | 0.00006                          | 0.022 ± 0.018                 | 29.8                            | 16.3                        |
| PLA150  | 2.07 ± 0.13                       |                                  | 0.008 ± 0.003                 | 28.7                            | 10.2                        |
| PLA200  | 1.92 ± 0.08                       |                                  | 0.005 ± 0.003                 | 25.8                            | 7.8                         |
| ABS50   | 1.97 ± 0.18                       |                                  | 0.020 ± 0.020                 | 41.1                            | 7.9                         |
| ABS100  | 2.00 ± 0.18                       | 0.28                             | 0.014 ± 0.010                 | 38.9                            | 4.5                         |
| ABS150  | 2.19 ± 0.13                       |                                  | 0.006 ± 0.004                 | 41.3                            | 8.3                         |
| ABS200  | 2.06 ± 0.16                       |                                  | 0.015 ± 0.016                 | 38.3                            | 6.7                         |
| PET50   | 3.18 ± 0.26                       |                                  | 0.005 ± 0.009                 | 32.3                            | 4.1                         |
| PET100  | 2.69 ± 0.22                       | 0.000001                         | 0.014 ± 0.010                 | 21.6                            | 13.4                        |
| PET150  | 2.68 ± 0.21                       |                                  | 0.017 ± 0.016                 | 40.2                            | 11.8                        |
| PET200  | 2.47 ± 0.20                       |                                  | 0.021 ± 0.014                 | 37.5                            | 12.1                        |

4 Conclusions and discussion

In the experiment, the dielectric properties of 3D printed objects made of three commonly used materials in FDM were evaluated. For PLA and PET-G, the results showed that permittivity slightly decreased with the increasing height of one layer. This may have been caused by larger air gaps between the lines and layers of the object. For ABS, the data were not statistically significant due to the bad printing quality of surface layers, so no evident dependency on height of one layer was found. The highest value of permittivity was measured on samples from PET-G, but it is still relatively small value for use in electronics industry for practical application like bushing condensers. An improvement of their permittivity may be achieved with some additives, for example the corundum powder ($\text{Al}_2\text{O}_3$). It is a task for further research, because the additives could also negatively influence the process of 3D printing (melting point, viscosity etc.). The slight dependence of permittivity on frequency indicates the polar character of the materials.

Measurement of dissipation factor was burdened with a considerable error. Therefore, no concrete result can be concluded. According to the observation during measurement, dissipation factor was rather an indicator of poor printing quality. The bigger dissipation factor, the worse the object was with rough surface or with more air gaps.

In general, the lower values of permittivity, compared to other measurements [7], [8], and relatively high deviations, especially for high printing resolution with height of one layer 50 µm, may indicate poor reliability and repeatability of manufacture by cheap printers using the RepRap concept. Therefore, the dependency of the dielectric properties of 3D printed objects on the printing resolution should be confirmed by further research using industrial printers.

In the case of dielectric strength measurement, ABS was evaluated as the most suitable material as insulation for electronic devices from all the examined materials. On the other hand, printing problems with ABS related to its properties during the liquid state cause unstable quality and no reproducibility. Therefore, no significant dependency of dielectric strength on the printing resolution was observed. The results of dielectric strength measurement for PET-G showed an unexpected but statistically significant difference between the printing resolutions. The dielectric strength of objects printed in high resolution (50 and 100 µm) was up to 2 times worse compared to
low resolution (150 and 200 µm). It can be explained by poor printability of PET-G for high resolution due to the lower speed of the filament movement through the extruder, different heating of the material and thus different properties in the liquid state that might cause worse adhesion to the substrate or cohesion of layers. Only the dielectric strength of PLA decreased with lower resolution, which was expected - the thickness of air gaps increased with lower resolution. Thus, the observed dependency proved decent printing repeatability of PLA.

In comparison with [4], similar results of dielectric strength were achieved for PLA and ABS. Both materials exhibit the dielectric strength above 30 kV/mm; however the dielectric strength of ABS is higher than PLA.

Based on acquired results, all examined materials are acceptable as insulation materials for lower voltage level devices. The use of higher printing resolution is recommended for increasing the dielectric strength. However, the improvement of the materials, respectively the printed objects, is required due to relatively small dielectric strength in comparison with commonly used insulation materials like transformer paper or XLPE. It can be achieved by better printing quality or admixtures.

Measurement error could be also caused by degradation by the environment. Thermoplastic materials are susceptible to moistening and photodegradation. Climatic tests of the objects and the influence of environment on the electrical and other properties might be also the subject of further research.

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