Study of electrical properties of 3D printed objects

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Abstract. *3D printing is an additive manufacturing process for building three-dimensional solid objects. This technology has use in many fields of industry, especially in rapid-prototyping. This project is focused on possibilities of use of 3D printing in electronics industry. 3D printed objects were investigated with a view to their electrical properties. The comparison of these properties for various common materials (PLA and ABS) was examined.*

The results showed that some of the properties of PLA are promising (relatively high dielectric strength, volume resistivity) compared to others (dielectric constant, loss tangent) that are not optimal for use in electronics industry and requires some improvements in form of additives. ABS has higher loss tangent than PLA, no significant difference in dielectric constant was found between ABS and PLA. Generally, an improvement of the electrical properties of these materials is required, for example by adding some additives to the base material.

Keywords

3D printing, 3D printed objects properties, FDM, measurement of electrical properties, rapid prototyping

1. Introduction

A relatively quick development in electronics industry requires quick and high-quality manufacturing of prototypes. Classic methods of manufacturing (mould pressing, cutting etc.) are time-consuming and expensive, so nowadays the new methods of additive manufacturing called 3D printing find use in prototyping. There are various technologies of 3D printing – SL (stereo-lithography), DLP (digital light processing), SLS (selective laser sintering), SLM (selective laser melting), LOM (laminated object manufacturing) and FDM (fused deposition modeling) [1]. It is possible to print a lot of various materials with 3D printing – polymer materials, metals, paper etc.; however the materials must have specific properties due to the used technology of 3D printing.

The process of FDM printing is depicted on Figure 1. A string of building material goes through an extrusion head consisted of a motor with idler rolls, a heat sink, a heater unit, a thermistor and a nozzle. The extrusion head extrudes the string on a bed, which can be also heated for minimization of problems connected with different coefficient of thermal expansion, and creates a model from digital data moving in three axis layer by layer. Nowadays, this type of 3D printing is wide-spread not only in area of industry, but also in households among DIY makers. The printers using RepRap concept (some of the printer parts are also 3D printed by another printer) became relatively cheap and interesting alternative for big, expensive industrial printers and even big companies use this concept of 3D printing in their prototype departments.

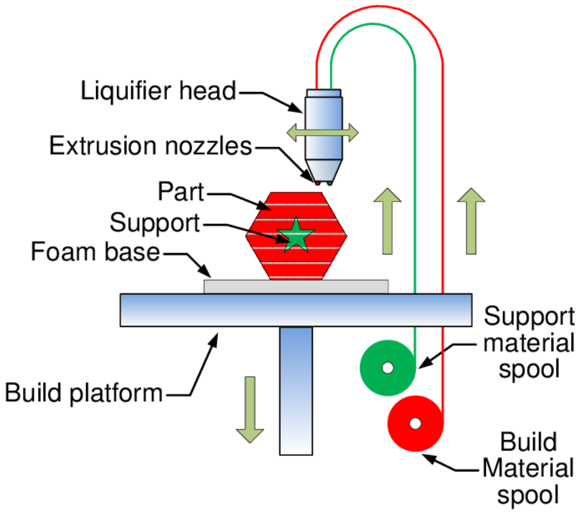

Figure 1. The principle of FDM printing proces [1]

The FDM method of 3D printing uses materials in form of string (filament) supplied on a spool. Generally, it can be any material that melts and then solidifies again, but there are some requirements on the melting process, viscosity of the material, coefficient of thermal expansion etc. Commonly used materials for this type of 3D printing are polymers. The most widely used materials are ABS (acrylonitrile butadiene styrene), PET-G (polyethylene terephthalate glycol-modified) and PLA (poly lactic acid).

Those materials are dielectric and they could be used in electronics industry – for example insulators or bushing condensers. An advantage of using 3D printing instead of standard methods of manufacturing is not only when speaking about prototyping, but it is possible to make forms that are difficult to reach.

With some proper additives, there is also possibility to print with a conductive or magnetic filament. These materials are used to print 3D printed antennas. This field of study is still at the beginning, due to not optimal properties of the materials. [2]

3D printed object has slightly different properties than object manufactured by standard method due to the technology. Between each lines in axis X and Y and layers in axis Z air gaps can occur. The size of these gaps is influenced by the 3D printer settings like the resolution (width of one layer) or Z axis offset. [3]

2. Methodology

The study deals with measurement of electrical properties of two common materials mentioned above – ABS and PLA. The samples prepared from these materials had transparent color (ABS and PLA) – materials without any additives or pigments - and white color (just PLA) – material with additional pigment called titanium white (titanium dioxide).

The samples were prepared on 3D printer DeeGreen from Be3D and MK2 from Prusa (Figure 2). The setting of a resolution of the printed object was 100 μm (width of 1 layer) for both printer as well as filling method (100 % filling density).

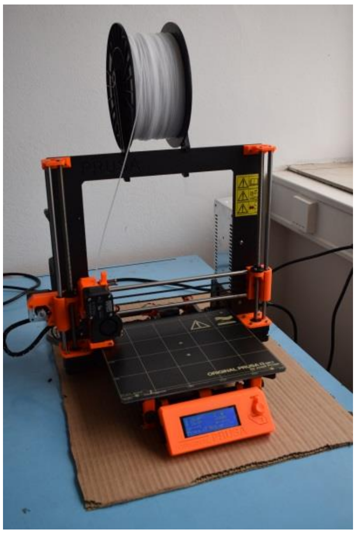

Figure 2. 3D printer Prusa MK2

For dielectric materials, there are four important parameters that define their use in electronics industry – dielectric constant (permittivity), loss tangent, volume resistivity and dielectric strength. All appointed parameters were examined in this study. Following paragraphs give information about each measurement.

2.1 Dielectric constant and loss tangent measurement

The samples for dielectric constant and loss tangent measurements were designed as circles with diameter 5 cm and width 0,5 mm and 1 mm (Figure 3). For a better contact in an electrode system, circular aluminum contact pads with the thickness about hundreds of nanometers were deposited by physical vapor deposition on both sides of the samples. Overall, 8 samples of each material (transparent ABS, transparent PLA and white PLA) were prepared and measured.

Figure 3. ABS samples: plain (left), with contact pads (right)

The capacitance and loss tangent of the samples were measured by RLCG meter Tesla BM 595 with the measuring frequency 1 kHz. For the measurement, a special electrode system was used (shown in Figure 4). Consequently, a value of the capacitance was used in formula for the dielectric constant calculation:

$$\varepsilon_r = \frac{C \cdot w}{\varepsilon_0 \cdot (\pi \cdot \frac{d^2}{4})} \quad (1)$$

where *C (F)* is the measured value of the capacitance, *w (m)* is the width of the sample, $\varepsilon_0 = 8{,}854.10^{-12}\ C^2 N^{-1} m^{-2}$ is the permittivity of vacuum and *d (m)* is the diameter of the sample.

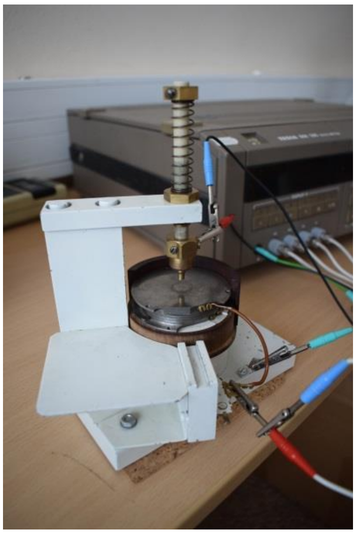

Figure 4. Dielectric constant measurement

Also, the measurement of the dielectric constant and loss tangent dependence on frequency was performed. The measurement was done by Agilent E4991A in the range from 1 to 100 MHz. Knowledge of the properties of the materials in this high range of frequencies could be useful for applications like 3D printed antennas.

2.2 Volume resistivity measurement

For the volume resistivity measurement the same samples, as for the dielectric constant and loss tangent measurement, were used.

The resistance was measured by programmable electrometer Keithley 617. Another special electrode system was used as it can be seen in Figure 5.

Figure 5. Volume resistivity measurement

Due to the long time needed for the relaxation, samples were measured for 10 minutes. It was observed that, the resistance rise significantly slowed down after this time. It can be expected that the value of the resistance increases if the measurement continued.

Then the resistivity was calculated:

$$\rho = \frac{\left(\frac{\pi \cdot D_{ef}^2}{4}\right)}{h} R \qquad (2)$$

where D_{ef} *(m)* is diameter of the sample, *h (m)* is the sample thickness and *R (Ω)* is the measured resistance.

2.3 Dielectric strength measurement

For the dielectric strength measurement, the samples were designed as flat rectangular strips with dimensions 38 mm x 145 mm and thickness 0,5 mm. Overall, 10 samples of white PLA were prepared and measured.

The sample was fixed in a special preparative with electrodes with diameter 6 mm (Fig.). The AC voltage (50 Hz) from high-voltage power source TuR-WPT0,8/65-GPT3/80 was applied to the sample. The value of breakdown voltage was measured by voltage probe Agilent 34136A and voltmeter MEIEX M-3850. Consequently, the dielectric strength (E_b *(kV/mm)*) was calculated with following equation:

$$E_b = \frac{U_b}{w} \qquad (3)$$

where U_b *(kV)* is the breakdown voltage and *w (m)* is the thickness of the sample.

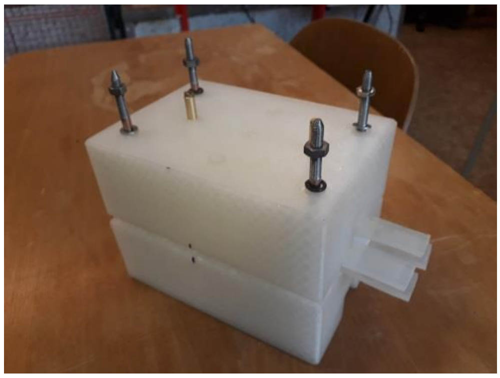

Figure 6. System for dielectric strength measurement

3. Results

The results of the dielectric constant measurement can be seen in Table 1. For both materials the dielectric constant appeared relatively small. In the case of ABS, the value of dielectric constant was about 3 compared to PLA dielectric constant that reached 2,7 - 2,9 in the case of transparent PLA and 3,1 - 3,2 in the case of white PLA with TiO_2. The additive in PLA had a significant influence on the dielectric constant of the sample. The results for transparent PLA corresponds to the measurement accomplished by colleagues from Portugal [4].

Table 1. Dielectric constant and loss tangent of ABS and PLA

Material	PLA				ABS
Color	white		transparent		transparent
Thickness (mm)	0.5	1	0.5	1	0.5
Dielectric constant ε_r (-)	3.1094	3.2107	2.6699	2.8514	3.0856
Loss tangent (-)	0.0053	0.0073	0.0050	0.0075	0.0269

The higher loss tangent was observed for transparent ABS. Its value ranged from 0,024 to 0,030 compared to PLA (transparent and white) loss tangent that ranged from 0,005 to 0,009. When the samples with various thickness were compared, the higher loss tangent was observed for the thicker ones. This fact can be explained by more air gaps between layers. No significant difference was found between transparent and white PLA.

In Figure 7 and Figure 8 the frequency dependence of the dielectric constant and loss tangent is shown. The difference between ABS and PLA occurred in this range of frequencies. The dielectric constant of the ABS began to decrease at lower frequencies with softer knee than transparent and white PLA. Furthermore, an increase of loss tangent of ABS in the measured range was greater than in the case of PLA.

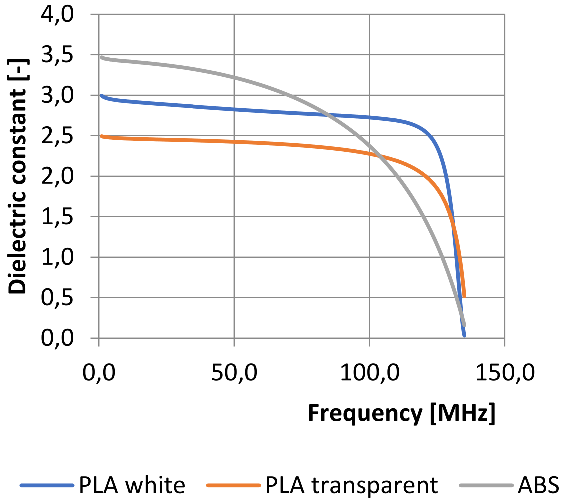

Figure 7. Frequency depedence of dielectric constant of ABS and PLA

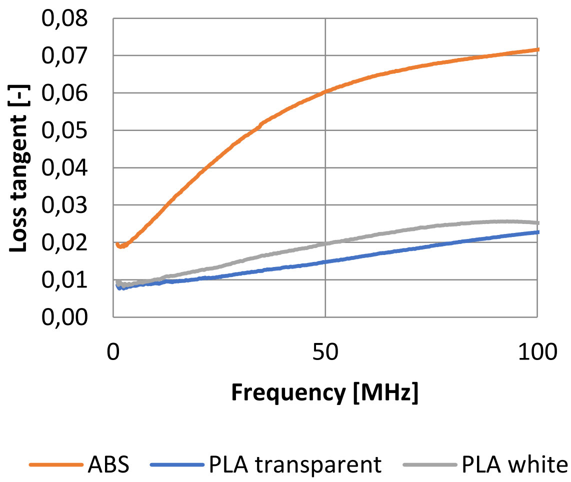

Figure 8. Frequency depedence of loss tangent of ABS and PLA

The results of volume resistivity measurement can be seen in Figure 9. There was no significant difference between transparent and white PLA, however the white PLA had slightly lower volume resistance because of the TiO_2. ABS had the lowest volume resistivity.

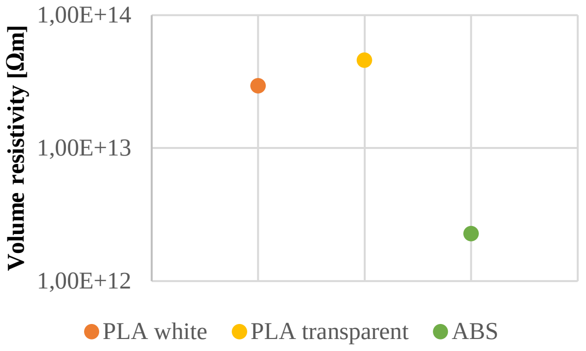

Figure 9. Volume resistivity of ABS and PLA

The dielectric strength measurement was difficult to complete due to the surface discharges that occurred during the increasing of the voltage. Therefore the relatively high observational error distorted the measured data. However, the highest observed value of dielectric strength for PLA was about 33 kV/mm.

4. Conclusion

The dielectric constant of the ABS and PLA are relatively small for use in electronics industry for practical application like bushing condensers. There could be improvement of their permittivity with some additives, for example the corundum powder (Al_2O_3). It is a task for further research, because the additives could also negatively influence the process of 3D printing (melting point, viscosity etc.).

When the loss tangent of the materials is compared, the PLA comes out in better light with loss tangent lesser up to 6 times than ABS. This is promising, but still a lot of space for improvement by some additional ingredients. Also the increasing tendency of loss tangent with increasing thickness of the objects is not desirable and discovers possibilities in technology improvement – how to eliminate air gaps between layers and lines of the building material etc.

It appears that PLA is rather an insulating material. The first result of relatively sophisticated measurement of dielectric strength that was about 33 kV/mm is very promising. Furthermore, the volume resistivity was up to hundreds of TΩm. For better measurement of dielectric strength it is planned to measure also the surface resistivity.

However, several problems could occur, when using PLA in insulating systems. This material is derived from corn starch and so it is biodegradable, unstable in time. The mechanical and other properties could change very markedly during aging. The solution could be also the development of proper additive to suitable adjustment of the PLA properties.

Other opportunities for further research could be with the opposite approach – reaching FDM printable conductive material. This could be achieved with PLA and the additive in form of metal powder (copper, aluminum, gold etc.) or with the development of new conductive polymers.

Also, an interesting topic for further research might be the influence of the printing resolution, temperature of the printing extruder and other printer settings on the dielectric parameters.

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