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Fully 3D printed rolled capacitor based on conductive ABS composite electrodes

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ABSTRACT

This paper presents a novel approach in the fabrication of rolled capacitors using a printable conductive ABS composite filament. On the contrary to conventional manufacturing of rolled capacitors, here a fused filament fabrication (FFF) technology, which allows a simpler and cheaper procedure of production is used. Also, a simple model of a 3D printed rolled capacitor is developed and the capacitance of the fabricated capacitor is calculated. The capacitance of the fabricated capacitor is measured in the frequency range from 100 Hz to 100 kHz. The measured capacitance is in good agreement with the calculated capacitance. It confirms the possibility of using conductive ABS composite filament for fabrication of 3D printed electrodes which could be formed passive device such as rolled capacitor or sensor for measuring liquid level.

1. Introduction

Recently, 3D printing as a one of the very emerging subsets of additive manufacturing technology (AM) has investigated comprehensively from materials and methods to applications and challenges [1,2]. 3D printing technology provides a design and a fabrication of complex 3D components on simple and low-cost manner without complicated post fabrication processes. Fabricating 3D object layer by layer has many advantages and it use in many fields of application: medical industry, machinery manufacturing and others. The use of 3D printing technology in electronics industry is in 3D printed components and printed circuit boards [3,4].

A fused filament fabrication (FFF) technology is a subtype of 3D printing which use thermoplastics in the form of a filament and offers wide possibilities for making 3D printed miniaturized systems [5]. The most frequently used FFF materials in electronics are acrylonitrile butadiene styrene (ABS) and poly lactic acid (PLA). Filaments of those materials are used for the fabrication of 3D printed antennas, 3D printed biofuels cell, sensors and other electronics devices, [6–9]. The thermoplastics polymers, ABS and PLA, are cheap (1 kg spool of FFF filament costs ~ 30–100$) and printed out with a relatively low cost FFF 3D printer (single nozzle FFF printer costs ~ 220$). Thus, the production of a 1 cm^3 device cost on the order of tens of cents if 3D printed with FFF [5].

By effectively extending the number of materials in 3D printing technologies, it will be possible to develop new processes in the fabrication of devices for different field of applications. Nowadays, electrically conductive polymer composites are obtainable for the 3D printer [10,11], which consequently expended the potential of 3D printing technology on the novel field of applications [12–14].

Until now, for realisation of printed capacitors were used ink-jet printing [15,16,17,18], aerosol printing [19] and screen printing [20,21,22] technology. There were reported studies on conductive ABS composite electrodes based on FFF technology for capacitor [23,24,25,26]. The realisation of 3D printed capacitor was in the form of parallel-plate capacitor [5,15,25], and interdigital capacitor [19,20,22]. So we decided to use FFF technology to develop a low-cost rolled capacitor since it allows to print in such shapes. FFF technique would advance the rolled capacitor fabrication: a) an expanding palette of processable materials (thermoplastics can be doped with functional materials, for example, titanate for use as the dielectric or conductive graphite for use as electrode; b) FFF process can be easily combined with other AM processes; c) simple, fast and economical operation (low cost printer, open-source software project, low cost feedstocks).

In order to fabricate a rolled (or wound) capacitor by the conventional (traditional) fabrication method, a plastic foil (polypropylene or polyester), a capacitor's paper and electrode foil (aluminum or tin) are sequentially superposed alternately, and then, they are wound to form a

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rolled capacitor [27]. A similar approach is used in the fabrication of a wound thinned glass capacitor [28]. 3D printing technology allow the fabrication process for the realization of a rolled capacitor to be much simpler and cheaper. Our approach is not based on a dielectric layer sandwiched between electrodes and then rolled them in the form of rolled capacitor. The differences in methodology of the rolled capacitor reported in this work, in compared to literature on other capacitor fabricated by FFF method are in design and one step fabrication (all electrodes are printed with one nozzle at the same time), in comparison with printing method in [5,25] with two printing nozzles.

The novelty of this investigation can be divided in two manners: first - the development of rolled capacitors using conductive polymer composite filament and, second - the fabrication of 3D printed capacitor electrodes using the FFF printing technology. To the best of our knowledge, there is no investigation of rolled capacitors fabricated using the 3D printing technique.

The design of the proposed 3D printed rolled capacitor based on conductive ABS composite filament is presented in Section II, together with a detailed description of the fabrication process. In Section III, the calculation of the capacitance of the 3D printed capacitor is presented. The measurement results together with discussion are presented in Section IV. Finally, the conclusion is given in Section V.

2. Design and fabrication process

To this day, different electrically conductive PLA and ABS filaments doped with metal nanoparticles, carbon nanotubes, graphite nanoparticles or graphene nanoparticles were investigated and characterized [5,29]. These materials provide a new methods for electrode fabrication.

Until now, many additive fabrication processes have been used for making curved conductive surfaces. One of these approaches is the printing of a dielectric curved surface and then added metallic layers, the second involves painting silver ink on the 3D printed surface, the third combines two technologies, FFF and direct write [13,30,31]. Using an electrically conductive polymeric composite filament gives the ability for the replacement of these multi-step processes with a single-step process. We decided to use electrically conductive ABS composite filament [6,29] for the development of 3D printed rolled capacitor, because ABS is a tough and strong material.

The development process for design, calculation, fabrication and measurement of the 3D printed rolled capacitor is presented and concluded through seven phases, shown on Fig. 1. The development process starts with numerical calculation using procedure which is shown in Section III. Ones is numerical calculation performed and required results are presented, the capacitor design is generated and exported via *.stl* file to the 3D printing machine. Next, the printing parameters are adjusted and prepared for the conductive composite filament and capacitor characteristics.

Prior the filament printing, the build platform has to be cleaned and deposited with glue. The fourth stage involves FFF printing the capacitor's electrodes. The fifth stage is assembled capacitor's electrodes and adding contacts. Finally, capacitor parameters, such as capacitance, resistance and quality factor Q, are obtained and compared with the calculated results.

The capacitor consists of two Archimedes spiral electrodes, denoted with grey (electrode 1) and black (electrode 2) colour in Fig. 2a. The 3D model of the rolled capacitor is shown in Fig. 2b was exported and printed using nano3Dprinter, A2200 [32]. The commercial conductive ABS composite filament from Saxon [33] was used as the printing material for the capacitor's electrodes.

The dimensions of the capacitor's electrodes and the distance between them, of designed rolled capacitor are shown in Fig. 2, where are inner diameter $d_0 = 10$ mm (inner radius $r_0 = 5$ mm), thickens of electrodes $t = 0.6$ mm, distance between electrodes $d = 0.6$ mm and height of electrodes $h = 10$ mm. Fig. 3 presents used 3D printer for fabrication (printing) designed rolled capacitor. Before a standard FFF printing process is started and filament is going through nozzle, filament was preheated over glass transition temperature (Tg). The 3D printing horizontal resolution, in the printing plane (x-y axis), depends of nozzle's diameter.

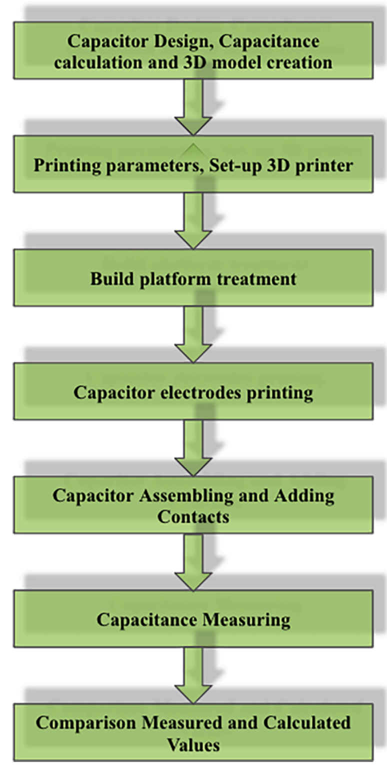

Fig. 1. Process flowchart of the proposed 3D printed rolled capacitor.

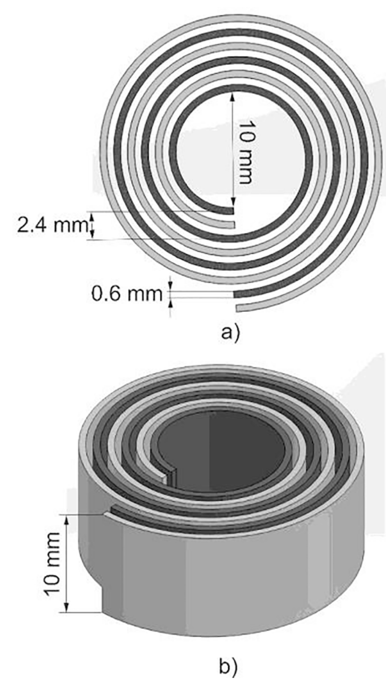

Fig. 2. Designed rolled capacitor: a) cross section and b) 3D model.

In our case, the printing nozzle has a diameter of 0.4 mm. The printing resolution on the z-axis (height of one layer) was set to 100 μm. A conductive ABS composite filament was heated on 230 ℃ in the heated build chamber and deposited onto a 90 ℃ heated build platform.

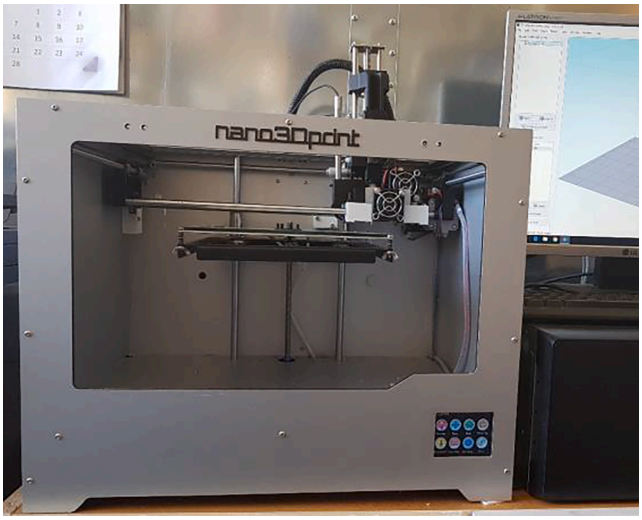

Fig. 3. 3D Multimaterials printer, A2200, manufactured by Nano3Dprint.

The photograph of the fabricated rolled capacitor is presented in Fig. 4. Contacts are added to the electrodes of the fabricated capacitor in order to connect it to the measurement instrument. A heating method (heated wire inserted in substrate) was used to produce solderless joint between the wire and the printed electrode [3].

The 3D printed capacitor's electrodes formed the air capacitor (dielectric between the electrodes is air) and this type of capacitor is denoted as type-1. The 3D printed capacitor's electrodes were immersed in water and this type is denoted as type-2. Table 1 presents geometrical dimensions of 3D model for the rolled capacitor.

Nowadays, on the market are FFF printers that can deposit different type of materials using independent nozzles. Monolithic FFF-printed resistors, capacitors, inductors, cantilevers and electro-hydrodynamic liquid ionisers were made with a dual extruder 3D printer MAKEiT PRO-M (MAKE iT, Inc. Alhambra, CA) [5]. Using this printer, we could be printed rolled capacitor with electrodes of conductive ABS and dielectric between them of non-conductive ABS material. Using dual-nozzle FFF printer, making possible monolithic fabrication of rolled all-ABS capacitor (it is denoted as a type-3).

3. Calculation of the capacitance of the 3D printed rolled capacitor

Calculation of the capacitance of the 3D printed rolled capacitor can do based on the formula for capacitance of cylindrical capacitor. Since d is, in our case, in fact very small compared to the radius of the cylindrical capacitor, the formula for the capacitance of a cylindrical capacitor gives

Fig. 4. The photograph of the fabricated rolled capacitor with added contacts.

Table 1
Geometrical parameters of designed rolled capacitor.

Height of electrodes	h = 10 mm = 0.01 m
Thickness of electrodes	t = 0.06 mm = 0.0006 m
Distance between electrodes	d = 0.6 mm = 0.0006 m
Inner radius of rolled capacitor	r_0 = 5 mm = 0.05 m

$$C = \epsilon_0\epsilon_r\frac{2\pi h}{ln(\frac{r_2}{r_1})} = \epsilon_0\epsilon_r\frac{2\pi h}{ln(1+\frac{d}{r_1})} \cong \epsilon_0\epsilon_r\frac{2\pi h r_1}{d} \tag{1}$$

where r_1 is the inner and r_2 the outside radius of cylindrical capacitor, $r_2 = r_1 + d$, ϵ_0 is the permittivity of vacuum, ϵ_r is the relative permittivity of dielectric between the electrodes, h the height of the cylindrical capacitor, d is the distance between the electrodes.

For a rolled capacitor, it is convenient to take the capacitance of one turn capacitor as a basic unit, which is

$$C_1 = \epsilon_0\epsilon_r\frac{hS}{d} \tag{2}$$

Where S is the circumference of the cylinder ($S = 2\pi r_1$). Based on these equations, the total capacitance of the two-turn capacitor is $3C_1$ and the total capacitance of the unrolled capacitor is $2C_1$, the three-turn capacitor is $5C_1$ and the unrolled capacitor is $3C_1$ [34].

The total capacitance of an n-turn capacitor is

$$C_n = (2n-1)C_1 \tag{3}$$

where n = 1, 2, 3…

In order to reduce the resistance of the printed electrodes we use thicker electrodes, which display different radii and circumferences

$$S_k = 2\pi R_k = 2\pi(r_1 + kd) \tag{4}$$

where is $k = 1, 2, \ldots 5n$. In our case, k = 1, 2, …., 15, (n = 3).

For average radius, k = 7, it is obtained average radius and average circumference, $R_S = 9.2mm$ and $S_S = 57.78mm$.

By measuring the distance between the electrodes of the printed capacitor (shown in Fig. 2), there is less distance between the electrodes, approximately 0.4 mm.

In order to calculate the capacitance of the fabricated capacitor with three turn, we used formula for the capacitance of a one turn capacitor with an average radius

$$C_1 = C_S = \epsilon_0\frac{2\pi R_S h}{d} = \epsilon_0\frac{S_S h}{d} \tag{5}$$

and then we inserted it in formula (3), for n = 3.

For the capacitance C_1, in our case, we get a value of 12.77 pF. The total capacitance of the rolled capacitor with three turn is $C = 63.9pF$ in the air (type-1) and $C = \epsilon_r \times 63.9pF = 5024pF$ in deionised water (type-2). Relative permittivity of water is 78.6.

Monolithic rolled all-3D printed ABS capacitor (which should be consist of two conductive ABS electrodes with nonconductive ABS dielectric between them) could be had $C = 2.74 \times 63.9pF \cong 180pF$ (type-3), where relative permittivity of nonconductive ABS is 2.74.

4. Measurement results and discussion

The validation of calculated capacitance of designed capacitor was examined by comparing the calculated results with values that we have received by measurement in laboratory conditions. Measurements were performed using the LCR meter Keysight U1730C and Impedance analyzer HP 4194A in the frequency range between 100 Hz and 100 kHz.

A decrease in resistance and capacitance is associated with frequency increase, and can be observed. Fig. 5 depicts the largest change in capacitance is at lower frequencies from 100 Hz to 10 kHz, and after that the capacitance starts to decrease slightly. The obtained values are 93,8 pF @100 Hz and 6 pF @100 kHz. Similar behaviour can be seen in Fig. 6,

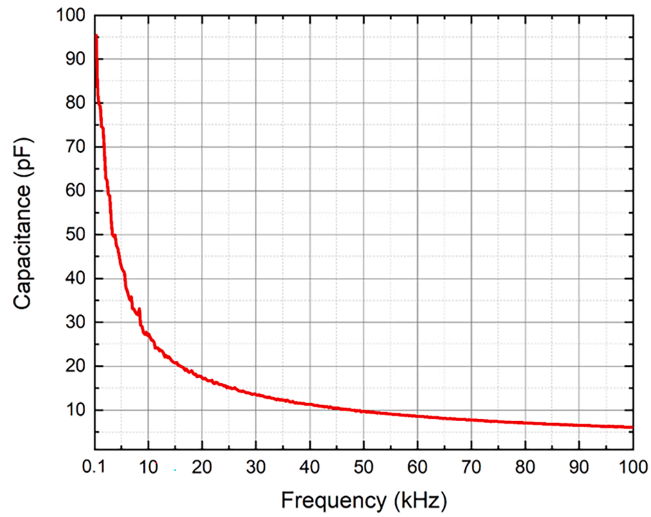

Fig. 5. Capacitance of 3D printed capacitor in air (type-1).

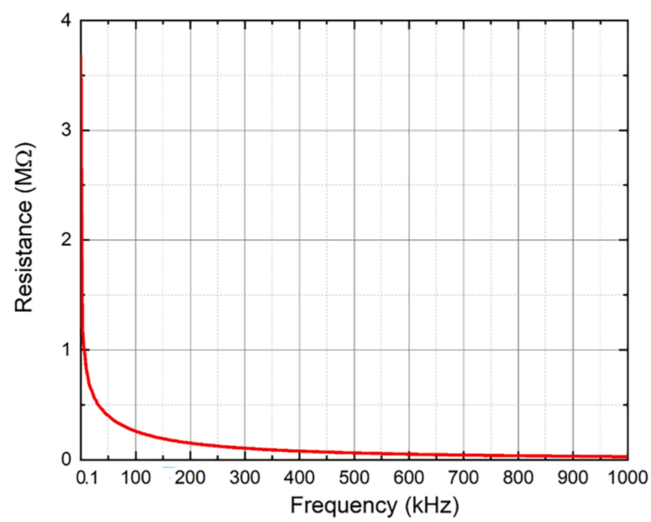

Fig. 6. Resistance of 3D printed capacitor in air (type-1).

for the frequency dependence of resistance. The resistance of the fabricated rolled capacitor decreases from 3.8 MΩ @100 Hz to 0.25 MΩ @100 kHz. The quality factor of the 3D printed capacitor is presented in Fig. 7.

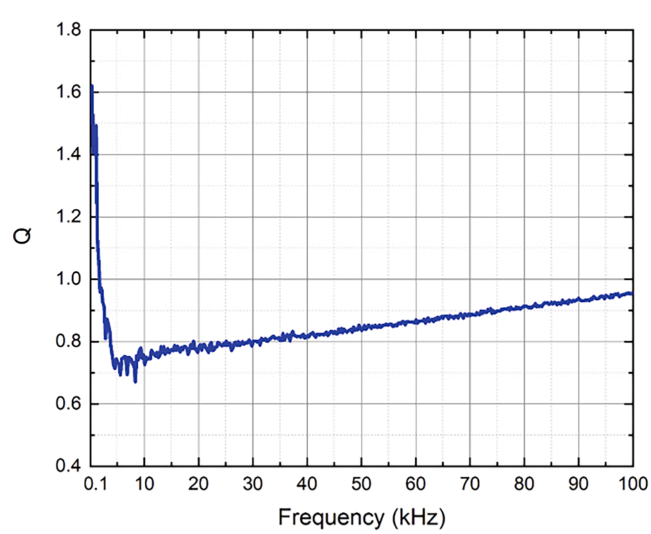

Fig. 7. Quality factor of 3D printed capacitor in air (type-1).

It shows the largest value at the frequency of 100 Hz. The largest change in the quality factor is at frequency range from 100 Hz to 5 kHz where its value is 0.7, and after that the quality factor starts to increase. The increase in Q-factor can be achieved with post processing. In [29], the effect of different post processing (such as, plasma and neosanding polishing) on 3D printed parts was demonstrated the enhancement of the electrical conductivity. This enhancement of surface electrical conductivity of post processed samples could be increase Q-factor, significantly.

A similar measurement was performed on the fabricated capacitor, which was immersed in deionised water. The measured capacitance of the fabricated capacitor is 5119.12 pF in the deionised water at 100 Hz. The calculated capacitances were compared with the measured values at the frequency of 100 Hz and good accordance was obtained, particularly in the case of liquid dielectric such as water. It offers the possibility of using these electrodes in sensor for measuring liquid level. It can be seen in Table 2.

The comparison of the capacitance per unit area of FFF-printed capacitors with the state-of-the-art capacitors is shown in Table 3. As it can be seen in Table 3, the performance of FFF-printed capacitors are approximately the same as what is published in the literature for other printing technologies [15,18,19, 35].

Traditional method fabrication of rolled or wound film capacitor is that, where two or more films/electrodes are spirally wound on mandrel (tube) to a predetermined number of turns, length, or capacitance value. The mandrel is then ejected from the winding, which is then further processed depending on the style and/or application of that particular part. Wound film capacitors can be further broken down into three basic categories: metalled electrode, discrete foil electrode and hybrid electrode [36].

Recently, it was reported [37] the traditional fabrication method of wound capacitors using 50 μm-thick flexible alkali-free glass wound into 125–140 mm-diameter spools. The capacitors exhibit a capacitance of 70–75 nF with loss tangents below 1%. Our capacitors have a diameter of 10 mm, and because of that have less capacitance values.

Commercial wound capacitors [38,39], available in non-inductively wound extended foil construction with oil-fill and standard tin-coated, oxygen-free solid copper leads have capacitance values order mF or μF.

Those results are promising and encouraging in implementation of FFF technology for low-cost component fabrication. However, a further improvement of printable conductive polymeric materials is necessary, especially regarding the value of conductivity. In [5], authors proposed a conductive PLA capacitor, to be feasible to implement capacitive, miniaturised, MHz RF filters for mass production.

5. Conclusion

This paper proposes simple manufacturing process using inexpensive FFF technology and electrically conductive polymeric composite filament for the prototype development. The obtained characteristics confirm the possibility of using conductive ABS composite filament for fabrication of 3D printed electrodes of a rolled capacitor or sensor for

Table 2
A summary of calculated and measured values of 3D printed rolled capacitor.

	Calculated capacitance C [pF]	Measured capacitance C [pF]	Q-factor	Frequency f [Hz]
Type-1	63,9	93,8	6,75	100
		6,2	0,95	100.000
Type-2	5024	5119,12	0,262	100
		338,34	1,86	100.000
Type-3	180	–	–	100
				100.000

Table 3
3D printed rolled capacitor: comparison with State-of-the-Art capacitors.

Reference	Geometry	Process	C [pF/mm2]	Maximum Q
[15]	square	inkjet	20	n.a
[19]-1	circular	inkjet	6.5	15
[19]-2	square	thin film	1.25	35
[5]	square	FFF	0.03	n.a
[35]-1	square	inkjet	0.74	n.a
[35]-2	interdigit	inkjet	4E-03	n.a
[18]-1	interdigit	aerosol	0.10	n.a
[18]-2	interdigit	aerosol	0.11	n.a
[18]-3	interdigit	aerosol	0.13	n.a
Type −1	rolled	FFF	0.14	6.75
Type −2	rolled	FFF	7.5	0.26

measuring liquid level. The thermoplastic materials allow the production of an infinite amount of geometrical shapes and sizes.

Electrical systems consist a large number of electronic components, ones of those are passive components. They need to be well designed and fabricated, to present good performance, stability, reliability and they should be suitable for cheap production for large scale.

The 3D printing process is simple and repeatable for mass production which provides a new direction in fabrication of high-performance components for portable and wearable electronic devices.

CRediT authorship contribution statement

Nelu V. Blaž: Design, Fabrication, Measurement. **Ljiljana D. Živanov:** Conceptualization, Methodology, Writing – review & editing. **Milica G. Kisić:** Design, Measurement. **Aleksandar B. Menićanin:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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