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Measuring the electrical resistance of a conductive material for a 3D printer

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***Abstract* — The introduction of this article briefly describes the measurement of electrical resistance. Subsequently, the method used to measure the electrical resistance is described, namely the measurement using by Wheatstone bridge and programmable LCR bridge HM8118. The article also describes the production of measured samples from its design to the final form making by using 3D FDM printing.**

***Keywords* — 3D FDM printing, electrical resistance, programmable LCR bridge, Wheatstone bridge**

I. Introduction To Measurement Of Electrical Resistance

By measuring the resistance, we determine how much the unknown resistance is greater or smaller than the unit of electrical resistance 1 ohm [Ω].The choice of a suitable measurement method depends on the size of the resistance measured, the required precision, the conditions under which the measurement is performed, the resistance character, and other.

Since the range of resistances to be measured in practice is relatively large, from 10^{-6} to 10^{14} Ω, the resistors are divided into three groups. The first group consists of the so-called small resistances, including resistors with a value between 10^{-6} Ω and 1 Ω. The second group consists of medium resistances with a value between 1Ω and 0.1 MΩ. The third group consists of large resistors with a value of 0.1 MΩ to 100 TΩ. Only certain measuring methods are appropriate for each group. However, looking at other aspects, some methods can also be used to measure the resistance of another group. Namely, if their value is close to the next group (e.g. 10 MΩ resistance can also be measured by the medium resistivity method, if we do not require a high precision, etc.).

The choice of measurement method will largely depend on the required accuracy. Accuracy requirements can range from 10^{-4} percent (standards) to ten percent in this case. Of course, in the case of a requirement for greater accuracy, we must assess the chosen method more strictly in terms of disruptive effects.

Based on the conditions under which the measurement is carried out, the external effects on the measuring instruments or on the total system of measurement used must be considered. It will include influence e.g. increased or reduced temperature, compared to the base temperature of 20 ° C, increased ambient humidity, vibration, the presence of strong magnetic or electric field and so on. [1]

II. Selection of The Appropriate Measurement Method OF Electrical Resistance

The purpose of this measurement is to verify the catalog values of the measured material given by the manufacturer. Specifically, it will be electrical resistance and specific electrical resistance. In our case, the measurement object is a conductive material for 3D printer called Electrifi. Electrifi Filament is a non-hazardous, proprietary metal-polymer composite that consists primarily of a biodegradable polyester and copper. Electrifi (see in Fig. 1) is available with a diameter of 1.75 mm and 2.85 mm. For the 1.75 mm filament, 100 g of the filament is 17 meters long. The filament extrudes at temperatures between 130-160 ºC with a recommended printing speed of 10-30 mm/s. Electrifi is shipped in a vacuum-sealed package with a desiccant packet. The filament should be stored in a cool, dry environment, and exposure to moisture should be minimized. Various factors had to be taken into

account when measuring the conductive material for the 3D printer. The manufacturer gives a specific electrical resistance with the value of 0.006 Ω.cm for this material. The electrical resistance measured by the manufacturer on a 109 mm long sample with a diameter of 1.76 mm was 2.5 Ω and a specific electrical resistance of 0.0056 Ω.cm was calculated. According to the manufacturer's data, we assumed that the electrical resistance of the material would be from the small resistance category. Therefore, it would be best to use the Thomson´s (Kelvin) bridge measurement method, which does not account for supply conductors resistance as well as the clamp resistance and is suitable for measuring small resistances. [1][2][3][4]

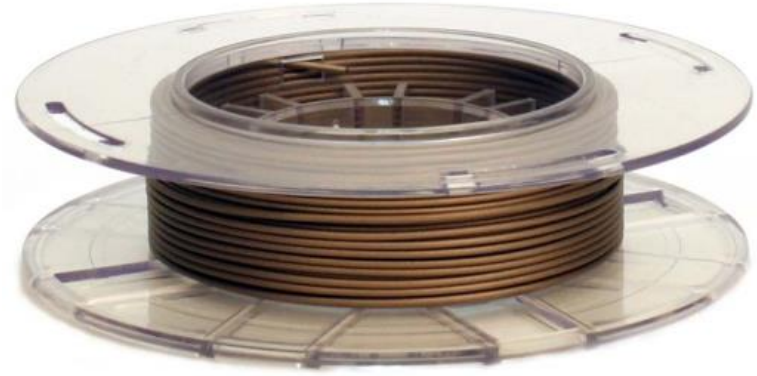

Fig. 1 The Electrifi conductive filament

However, in this measurement, the so-called tapping (using the meter's thin terminals) of the measured voltage at a certain distance in a short time is required. This was not possible in this case since the transition resistance between the thin connectors of the measuring instrument was so great that it was not possible to subtract the value of voltage. The material delivered by the manufacturer in the form of a coil does not exhibit suitable electrical conductive properties. Since it was not possible to measure the electrical resistance of the material in its standard form using a common measuring instrument, a programmable LCR measuring bridge was used which can be seen in Fig. 2. Using a LCR programmable bridge, we measured a standard sample of 85 mm with a diameter of 1.75 mm. The measurement was made via direct connection of the clamps to the material. We measured the electrical resistance of 221.6 Ω. Another measurement was made by attaching the clamps to a special agent, in which the material was attached. Material was screwed into the agent and we measured an electrical resistance of 381.18 Ω. We can see both examples of measuring in the Fig. 2. [5]

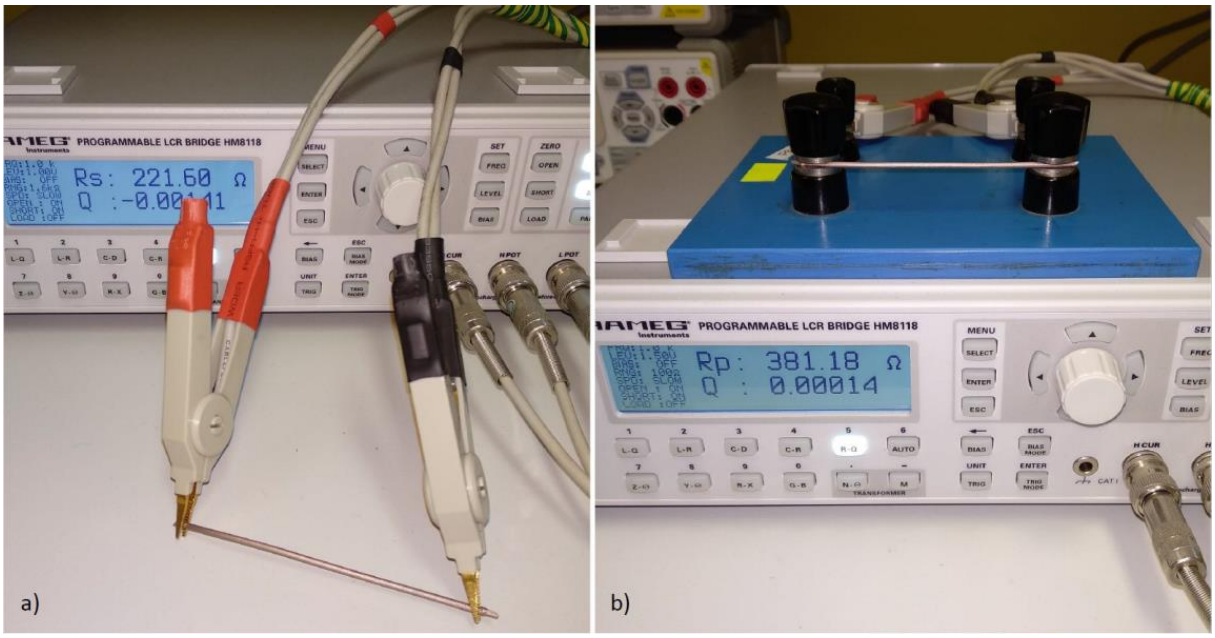

Fig. 2 a) The measurement of Electrifi filament sample in default form with 1,75 mm diameter, b) The measurement of Electrifi filament sample in default form with 1,75 mm diameter mounted into a special agent.

Due to the high value of electrical resistance on the material in this basic shape, it was necessary to process the material appropriately for next measuring. Thus, samples were designed using CAD software, and printed with a 3D printer. By 3D printing, the material was heated up to the desired temperature resulting in the change of the materials internal structure. By disrupting the inner structure, the individual copper particles gained motion, resulting in a change of the electrical resistance of the material. After printing of the proposed samples, it was possible to realize the measurement of electrical resistance by a suitably chosen method. The design of the printed samples and the detailed measurement procedure using bridges will be described in the following chapters.

III. THE DESIGN AND PREPARATION OF SAMPLES

By measuring on a sample of material in standard form, we found that the measured data did not absolutely match the data reported by the manufacturer. This may be due to a number of factors such as: excessive material moisture during storage and dispatching (even though it is supplied in a hermetically sealed foil with a moisture absorber), a change in the internal structure of the material (bending, heating to a certain temperature) and other undesirable effects in the surroundings. Electrifi is a metal-polymer composite consisting mainly of biodegradable polyester and copper. The copper particles contained in the composite can also be arranged inhomogeneously, which fundamentally changes the electrical conductivity or electrical resistance of the material. Therefore, it was necessary to heat the material to the desired temperature and perform measurements on a suitable sample printed, using 3D printer. To print a sample using the 3D printer, you need to perform some of the operations described below:

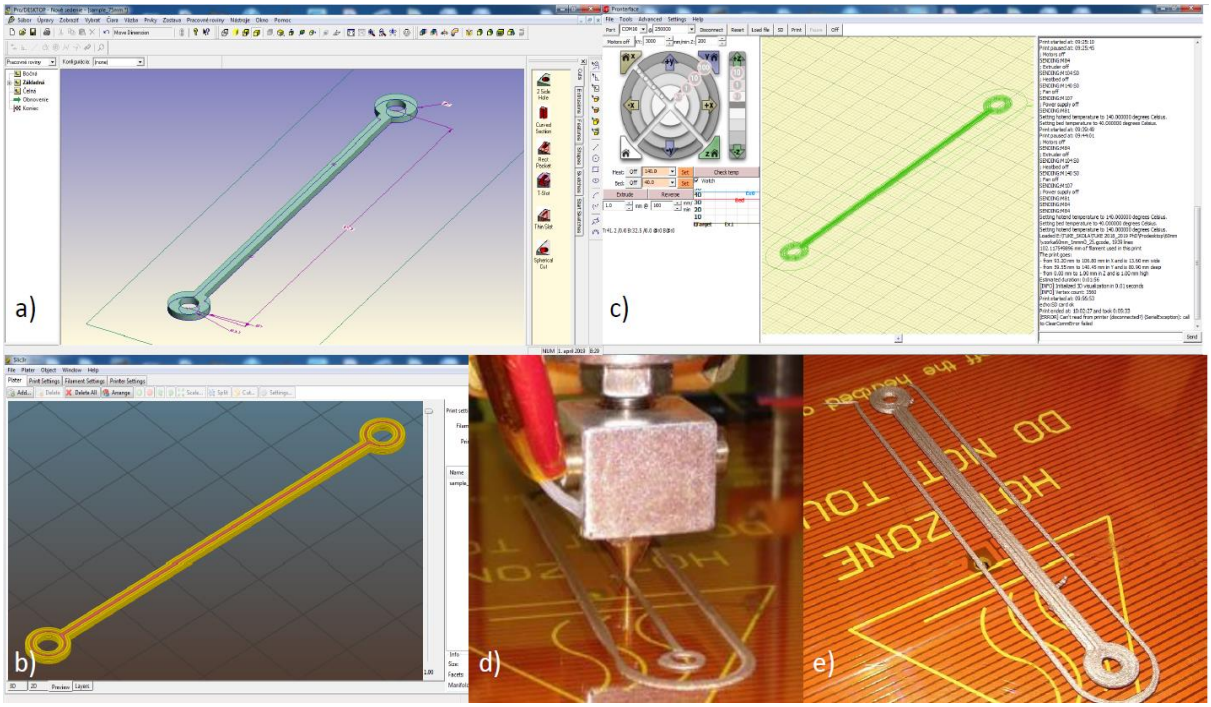

Fig. 3 a) CAD design of the sample, b) parameters set in CAM software, c) g-code file imported to the Pronterface, d) Process of printing the sample, e) Printed sample.

In the Fig. 3 a) we can see the design of measuring sample designed using CAD software. The sample has a cuboid shape with dimensions of 2.8 mm x 75 mm x 1.1 mm. These samples were printed in 2 pieces, with different 3D printer settings. Next, using CAD software, we exported the file to STL format. Subsequently, the STL format model was processed by CAM software called Slic3r, where individual printing parameters were set and the g-code file was created. The slic3r environment with the imported model can be seen in the Fig. 3 b). It is still necessary to upload a g-code file to a program called Pronterface, which can be seen in Fig. 3 c). This program controls the 3D printer. The diameter of nozzle 0,8 mm was used to print the samples. This diameter of nozzle is also recommended by the material manufacturer. [4]. The nozzle and the printing process can be seen in Fig. 3 d). Printed samples can be seen in Fig. 4.

Fig. 4 3D printed samples

For the production of the sample, the 3D FDM printer produced by us, which can be seen in Fig. 5 was used. A test measurement using a programmable measuring LCR bridge was performed on the printed samples. The electrical resistance that falls into the group of medium resistances was measured. Therefore, we used the Wheatstone Bridge to determine the exact resistance of this material. The measurement of the electrical resistance of the printed samples using bridges will be described in more detail in the next chapter.

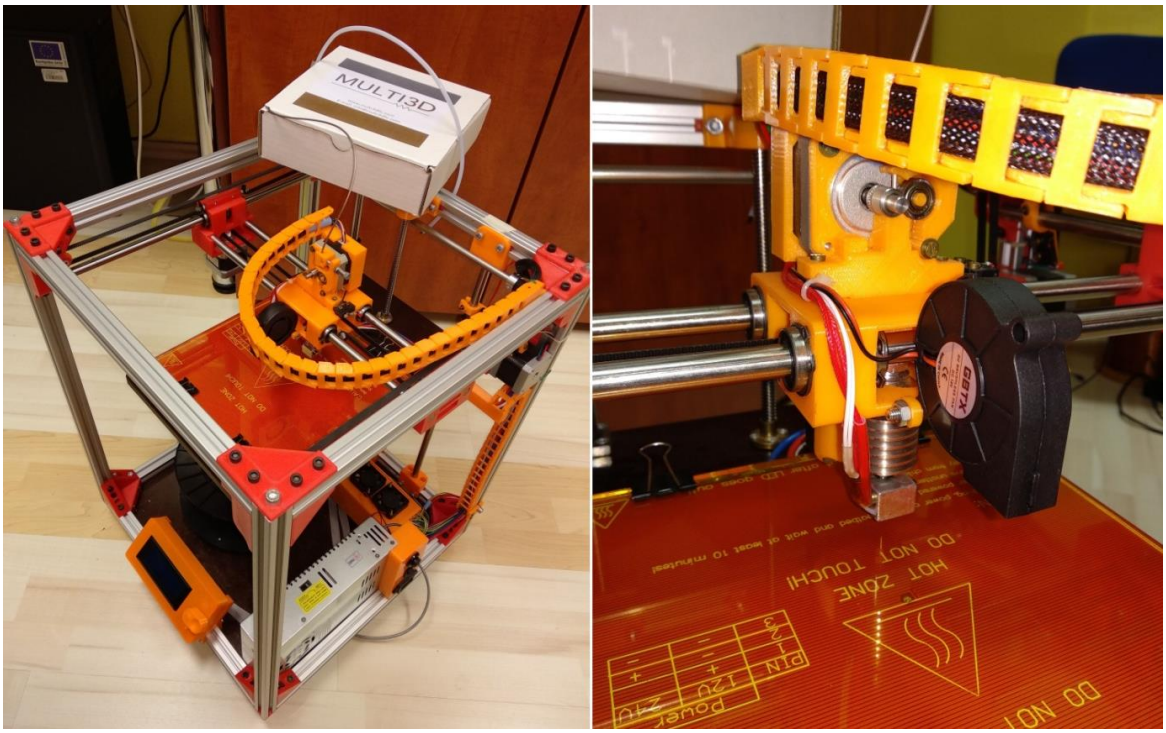

Fig. 5 3D printer

IV. Realization of The Measurement

Accurate measurement of electrical resistance is mostly realized by direct current. Many of the methods used here have been known for a long time. The most well-known measuring method using bridges was proposed in 1843 by Sir Charles Wheatstone. The Wheatstone bridge is best suited for measuring of medium resistances, where the resistence of supply conductors as well as clamp resistance is not taken into account. The realization of the measurement of electrical resistance using the bridges will be described in the following lines.[2]

A. Measurement of electrical resistance using HAMEG - programmable LCR bridge HM8118

After switching on the device, the first step is a short-circuit calibration at a preselected frequency of 1.0 kHz. After turning the instrument on, the first steps are the open circuit and the short circuit calibration procedures at the preselected frequency of 1.0 kHz because the measurement cables HZ184, in conjunction with the terminals, due to their design, show a stray capacity, a residual inductance and

a residual resistance which impair the accuracy of the measurement results. In order to minimize these influences, the compensation of impedance measurement errors caused by adapters and cables is necessary. For short-circuit calibration, both measuring terminals were connected together and then shorted using the appropriate button. An automatic equivalent circuit selection has been selected; the LCR measuring bridge automatically selects an equivalent circuit that is best suited for accurate measurement depending on the connected passive elements. The equivalent circuit is representing the measuring circuit. Typically, low impedance components (capacitors, choke coils) are measured using an equivalent serial connection circuit while high impedance components (e.g., resistors) will be measured using a parallel equivalent circuit. Using two terminals, a sample attached to the LCR bridge was measured and the electrical resistance value was read. This measurement was performed 3 times for both material samples at constant frequency at the voltage of 1V and the temperature of 20°C. In Fig. 6, we can see the realized measurement. [5]

Fig. 6 The measurement of electrical resistance by LCR programmable bridge HM8118.

The specific electrical resistance of the individual samples was determined using the following equation (1).

$$\rho = \frac{R_X \cdot S}{l} = \frac{16{,}197 \cdot 3{,}08}{75} = 0{,}6652\ Ohm.mm = 0{,}0665\ \Omega.cm \qquad (1)$$

Using the equation (2), we calculated the content of the printed samples.

$$S = X \cdot Z = 2{,}8 \cdot 1{,}1\ = 3{,}08\ mm \qquad (2)$$

The measured electrical resistance values of the samples are shown in Table 1.

Table 1 Parameters for 3D printing of sample and measurement of electrical resistance by programmable LCR bridge HM8118

	3D printing			**Measurement electrical resistance – LCR bridge HM8118**				
SAMPLE - layer height	**Dimension $X \times Y \times Z$ [mm]**	**Print speed [mm/s]**	**T_P [°C]**	**T_A [°C]**	**R_X [Ω]**	**Average R_X [Ω]**	**ρ [Ω.cm]**	**U [V]**
0,2 mm	2,8 × 75 × 1,1	10	140	20	20,775	20,771	0,0853	1
					20,772			
					20,766			
0,25 mm	2,8 × 75 × 1,1	10	140		16,220	16,197	0,0665	1
					16,200			
					16,170			

ρ - Electrical resistivity, specific electrical resistance or volume resistivity, T_P - Temperature of the material printing, T_A - Temperature of the material printing, R_X - Measured (unknown) electrical resistance.

B. Measurement of electrical resistance using Wheatstone bridge

Wheatstone bridge measurement is one of the most accurate and widespread measurement methods. The measurement is more accurate if the individual components of the circuit are more accurately manufactured and then measurement reaches accuracy of the tenth of a percent. The sensitivity of the measurement depends on the source voltage and the galvanometer sensitivity. There are several versions of the Wheatstone Bridge, e.g. operating bridge (for rough measurement), pin, crank bridge (for accurate laboratory measurement). For our measurements, a crank MTW bridge was used for accurate laboratory measurement. [1][2]

After connecting the galvanometer (G), the power supply (B) and the unknown resistance (R_X) to the corresponding terminals of the laboratory Wheatstone bridge (M), the circuit is connected as shown in the scheme in Fig. 7.

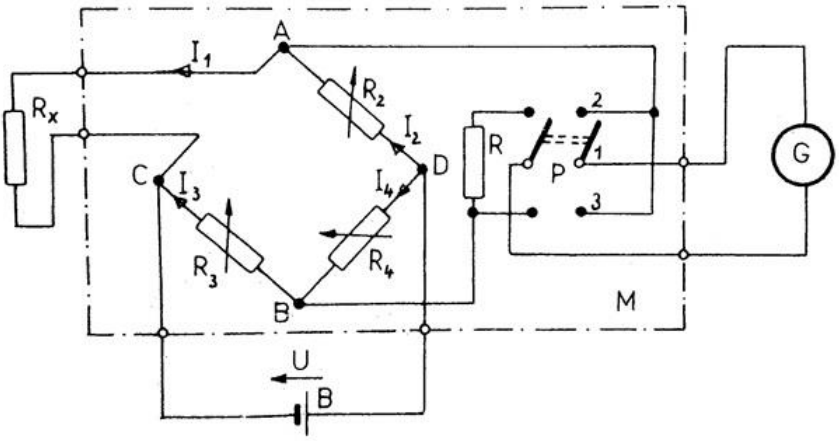

Fig. 7 Wiring diagram for measuring of electrical resistance using Wheatstone bridge

The measurement was carried out on two samples 3 times at the voltage of 1V and the temperature of 20°C. The measurement with Wheatstone bridge is shown in Fig. 8.

Fig. 8 Wiring the instruments of measurement of electrical resistance using Wheatstone MTW bridge in laboratory

In Table 2 we can see all measured values for two printed samples with different heights of one layer (0.2 mm and 0.25 mm). The parameters used for printing of the samples are written in the left part of the table. The right part of the table contains a parameter for measuring of electrical resistance using Wheatstone bridge. The calculation for the determination of electrical resistance of the measured sample is obtained by the equation (3).

$$R_X = \frac{a}{b} \cdot R = \frac{10}{1000} \cdot 1785 = 17{,}85\ \Omega \tag{3}$$

The specific electrical resistance of the individual samples was determined using equation (4). Using the equation (2) we calculated the content of printed samples.

$$\rho = \frac{R_X \cdot S}{l} = \frac{17{,}82 \cdot 3{,}08}{75} = 0{,}732\ \Omega.mm = 0{,}0732\ \Omega.cm \tag{4}$$

Table 2 Parameters for 3D printing of samples and measurement of electrical resistance by Wheatstone bridge

	3D printing			**Measurement electrical resistance – Wheatstone bridge**							
SAMPLE - layer height	**Dimension $X \times Y \times Z$ [mm]**	**Print speed [mm/s]**	**T_P [°C]**	**T_A [°C]**	**a [-]**	**b [-]**	**R [Ω]**	**R_X [Ω]**	**Average R_X [Ω]**	**ρ [Ω.cm]**	**U [V]**
0,2 mm	2,8 × 75 × 1,1	10	140	20	10	1000	1785	17,85	17,82	0,0732	1
							1783	17,83			
							1778	17,78			
0,25 mm	2,8 × 75 × 1,1	10	140				1452	14,52	14,47	0,0594	1
							1445	14,45			
							1443	14,43			

ρ - Electrical resistivity, specific electrical resistance or volume resistivity, T_P - Temperature of the printing material, T_A - Temperature of the printing material, R_X - Measured (unknown) electrical resistance.

V. Conclusion

In this article, it was found out by the measurement, that the measured material parameter specified by the manufacturer does not match our measured values. To verify the correctness of the results, the measurement was performed by two methods described in this article. By comparing the manufacturer's parameters and our measured values, it is clear that the specific electrical resistance is one tier worse than the manufacturer told. Thus, we can conclude that this material could have been: made incorrectly, damaged in transport by excessive moisture or the manufacturer simply does not mention the real parameters of the material. Since there is no better metal-polymer composite available on the market than this one, we are forced to resort to a different solution for realization of the technical coil used by 3D printing.

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