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Electrostatic Properties and Characterization of Textile Materials Affected by Ion Flux

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This work analyzes the opportunities of wider characterization of textile materials, fabrics, upholstery fabrics, fibers, yarns or others, which may accumulate electric charge. A non-contact way for electrostatic properties measurement based on affecting those materials by ions with positive or negative charge is described. The method allows to measure simultaneously the time dependences of the surface voltage and the electric charge during the charging process and the time dependences of the surface voltage during the discharging process. From the measured dependencies the following set of parameters was measured or calculated: the surface voltage limiting value, the surface voltage semi-decay time, the maximum deposited charge, the layer capacitance, the energy of the accumulated charge and others. The surface voltage distribution measurement method when the investigated textile material is affected by ion flux was also described. To verify the applicability of the proposed methods for characterization of textile materials in order to determine the above-mentioned parameters of cotton, linen, wool, viscose, acetate, polyester, polyester coated with polytetrafluoroethylene, a series of experiments were performed. The surface voltage distribution measurement method based on affecting textile materials by ions with positive charge was described and a surface voltage distribution of a polyester-cotton upholstery fabric produced by a Jacquard mechanism was presented. The performed experiments demonstrate the possibilities of method application for comparison of the electrostatic properties of different textile materials used for the same tasks or the same materials produced by different technological processes.

Keywords: textile materials, fabrics, upholstery fabrics, static electricity, surface voltage measurement, charge measurement, surface voltage distribution measurement.

1. INTRODUCTION

It is known that unintended consequences of electrostatic discharge can cause serious problems in a number of situations, can damage products in electronic assembly, impair the quality of products, create problems of workers' health and safety, and many others [1]. Textile materials (textiles, fabrics, upholstery fabrics) are widely used and are known for their abilities to accumulate electric charge. So to avoid the mentioned undesirable effects textile material must be developed so that they would have acceptable electrostatic properties. Textile materials behave like an electric charge accumulating capacitor where the dielectric material is composed of fibers and air gaps [2]. The presence of air gap in fibers and textiles can be modelled as a mixed-type capacitor dielectric layer that specifies the electrical properties of textile materials. Consequently, a broad range of electrical properties of fabrics or textile products depends on the topography, compactness, thermal and chemical treatment of the final product but also depends on atmospheric conditions where the textile products is used or where the electrical properties are measured. Consumers of textile materials are looking for products developed with acceptable electrostatic properties. So those properties must be measured and examined.

Most materials used for textile products are electric insulators and the main measured electric parameter is the surface resistance that varies extremely, in the range of 10^{13} Ω to 10^{6} Ω [3]. As it is well-known, high surface resistance materials can be electrostatically charged. An accumulated electric charge has the ability to generate and retain an electrostatic field of significant magnitude. This electric field can be detected as a surface voltage that can be measured. Thus the surface voltage and voltage dynamics can reflect the main electrostatic properties of the examined textile material.

Widely used methods for measuring electrostatic properties of textile materials are presented in the European standards, which describe the test methods for measuring surface resistivity [4], electrical resistance through a material [5] and electric charge decay [6] and is applied in textile materials research and evaluation laboratories [7]. Measurements of electrostatic properties are also described in Chinese standards for testing static properties and static voltage semi-decay of textile materials [8] and static electricity testing of textiles [9]. A closer examination of test methods shows that measurement of electrostatic parameters of textile material are based on methods, which in some cases do not provide sufficient information about tested products. The method described below has certain advantages because the sample is affected by ion flux and that makes it possible to measure the integral surface voltage and the amount of charge simultaneously that contribute additional information on

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textiles. The method may be adapted also for measurement of surface voltage distribution. Therefore, in this article we discuss a technique of direct measurement of electrostatic parameters and also we discuss the possibility of applying it to investigate electrostatic properties of textile materials.

2. EXPERIMENTAL

2.1. Measuring method and instrumentation

The measuring method described below takes the textile materials electrical properties into consideration. The method is based on the investigation of the sample surface electrical parameters when a sample is affected by ion flux generated by a corona charging device [11 – 13]. The applied instrumentation is able to measure the time dependences of the accumulated amount of electric charge of the sample and the surface voltage when the sample is affected by ion flux or not. There are two different measuring processes. Process 1: when the sample is affected by ion flux an amount of electric charge Q is measured and in the time interval when the deposition of ions is stopped, the surface voltage V is measured; the amount of electric charge and surface voltage are measured one after another periodically, and the charging process of the examined sample is investigated. Process 2: after a time interval when the sample was affected by ion flux and was electrically charged, the surface voltage V dependence on time t is measured. In the latter case measuring periodically the surface voltage of the examined sample when the corona charging device is switched off, the electric discharge process is investigated. The experiment may be carried out affecting the sample to positive or negative ions generated in humid air at atmospheric pressure by a corona charging device [10, 14]. An important feature of this method is that the examined textile material sample is not influenced by external force pressure. The structure of the experimental set-up in a simplified form is shown in Fig. 1.

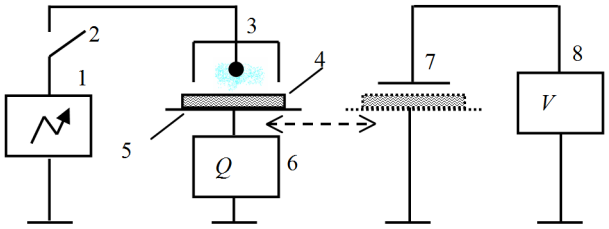


Fig. 1. Block diagram of surface voltage and deposited electric charge measuring instrumentation: 1 – high voltage power supply, 2 – high voltage connector, 3 – corona charging device, 4 – test sample, 5 – sample substrate, 6 – electric charge meter, 7 – surface meter sensor, 8 – surface voltage meter

The charging process is used to evaluate the physical properties of the samples. When the charging process is carried out, i. e. when the time dependence of the amount of electric charge Q and the surface voltage V are measured simultaneously (Fig. 2), the surface voltage dependence on deposited electric charge (V-Q) is obtained (Fig. 3). Theoretically, the dependence of the surface voltage of an ideal dielectric layer on the amount of electric charge accumulated on its surface must be linear, which is not the case in the real situation. The mentioned dependence becomes clearly non-linear when the surface voltage approaches the limiting value V_{max}. This limiting value depends on corona charging device voltage V_{cv} and on the non-linear dependence of leakage current trough the investigated sample which can cause destructive and irreversible processes in the investigated sample when the surface voltage is increased. The (V-Q) dependence also depends on positive or negative electric charge deposited on the sample surface. From the linear part of the (V-Q) dependence, the capacitance C of the investigated sample can be calculated ($C = \Delta Q / \Delta V$, see Fig 3), the maximum deposited electric charge Q_{max} when the surface voltage reaches the limiting value can be found and finally the accumulated electric charge energy W_Q can be calculated ($W_Q = C \cdot V_{max}^2 / 2$). The measurement process more detailed is described in [12, 13].

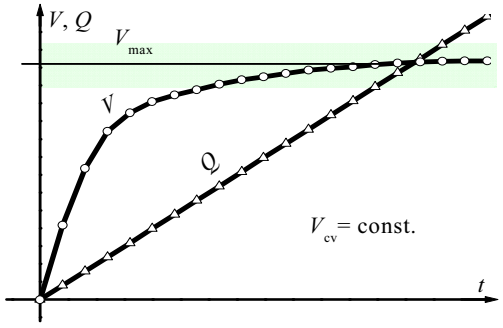


Fig. 2. The textile material charging process: time dependence of surface voltage V and electric charge Q, when a textile material is affected by ion flux at a fixed corona charging devices voltage V_{cv}

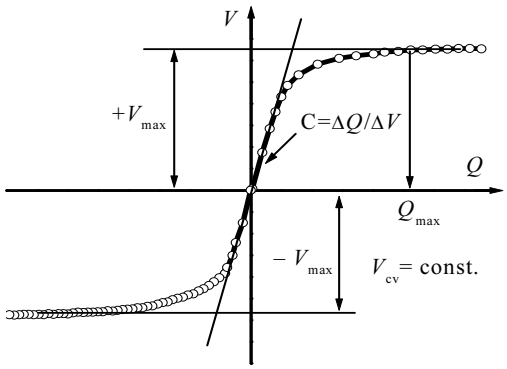


Fig. 3. The dependence of surface voltage V on deposited electric charge Q calculated from the date of Fig. 2

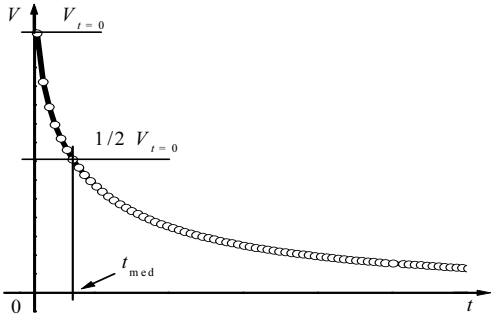


Fig. 4. The textile material discharging process: surface voltage V dependence on time t when the corona charging device is switched off

The discharging process is used to evaluate the antistatic performance of the samples. When the discharging process is carried out, the surface voltage dependence on time (V-t) is obtained (Fig. 4). Theoretically, the dependence of the surface voltage on time of an ideal dielectric layer is an exponential curve. In our case it is not exponential, because often the investigated material has a complex composition. But for practical purposes the surface voltage semi-decay time t_{med} is calculated under the assumption of the exponential dependence. To evaluate the discharge rate of the tested material, the period of time during which the surface voltage is reduced by half is determined from the V-t dependence (Fig. 4). The shorter the semi-decay time t_{med} , the better the antistatic ability of the samples composition.

Here are a few parameters of the measuring instrumentation. The maximum corona charging devices voltage V_{cv} is about 9.0 kV, the maximum value of current generated by the corona charging device is 100 μA. The measuring interval of the electric charge meter is from 10^{-4} C to 10^{-10} C (the relative error of measurement is ±5 %). The surface voltage measuring interval is from 30 V to 3500 V (the absolute measurement error is ±7.5 V). In the described instrumentation, the dimensions of a test sample are 51 mm × 46 mm and the measurement aperture area – 40 mm × 30 mm. The test sample must be evenly placed on the substrate surface.

2.2. Surface voltage distribution visualization technique

The method when the investigated material is affected by ion flux is also applicable for textile materials surface voltage distribution visualization. The voltage distribution on the whole surface of the investigated textile material is measured fixing it on a mechanically rotating cylinder. A step-by-step ring scanning mode for surface voltage measuring is applied and the measured data are collected and visualized on a computer. The structure of the experimental set-up in a simplified form is shown in Fig. 5.

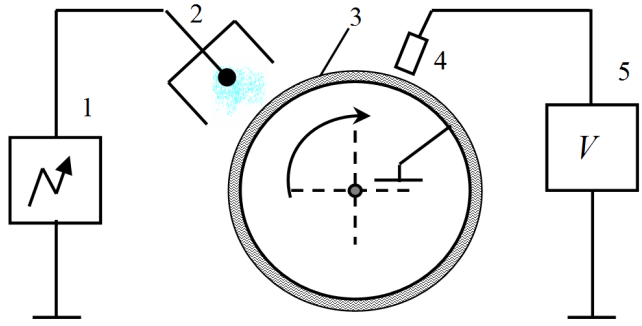


Fig. 5. Block diagram of surface voltage distribution measuring instrumentation: 1 – high voltage power supply, 2 – corona charging device, 3 – test sample on the rotating cylinder (drum), 4 – surface voltage meter sensor, 5 – surface voltage meter

The main technical parameters of surface voltage distribution measuring instrumentation are the following. The diameter of the conductive cylinder made of aluminum alloy is 120 mm. The scanning surface is 250 mm × 210 mm. The length of one scanned line is 250 mm, the scanning step is about 1.25 mm and so the full surface is scanned in 168 lines. The time required for one line scanning is about 1.0 s and the full surface is scanned in 3.5 min. The corona charging device voltage V_{cv} can be selected from 4 kV to 9 kV. The maximum value of a current density generated by a corona charging device is 30 μA/cm^2. The surface voltage is measured with a contact-free precision surface voltage meter (by TREK, INK. company) Trek model 400 with a vibrating reed probe sensor. The voltage measuring range of this surface voltage meter is up to ±2000 V, the measurement accuracy is 0.05 % and the resolution power is about 2 mm at a gap of about 2 mm (standard probe 400P-E). The diameter and the speed of rotation of the cylinder, the distance between the corona charging device and the surface voltage meter probe are chosen so as to ensure acceptably small decrease of the surface voltage after switching off ion flux. In the described instrumentation the surface voltage is usually measured at 0.14 s after the measuring place leaves the corona treatment zone.

3. EXPERIMENTAL RESULTS

3.1. Selected research textile materials and preparation of samples

To verify the described method for measuring electrostatic properties of textile materials affected by ions two types of textile materials were selected. The first group was textile materials based on one type of natural or man-made yarns and the second group consisted of textile materials based on natural or man-made yarn assemblies. The experiments were carried out with the following textile materials. Cotton is a natural fiber that readily absorbs oxygen and is flammable. To reduce flammability the cotton fiber is chemically treated, which changes its physical and electrostatic properties. Sometimes cotton is also blended with linen in order to improve the fiber properties. Linen is a natural fiber that can absorb and lose water quickly, so the measured results depend on the environment humidity. Wool is one kind of natural animal fiber that consists of particular proteins. Wool is flame resistant and has excellent moisture absorption properties. It is known that its electrostatic properties are different from those of other natural fibers. Viscose is a manufactured by transformation of natural polymers and does not build up static electricity. Viscose is produced of wood cellulose in a combination of natural and man-made components. Acetate is a man-made cellulosic fiber. It has optimal moisture absorption and a quite high electrical resistance. Acetate is used on its own or with other natural or synthetic fibers. Acrylic is a man-made organic fiber made from a synthetic polymer composed of at least 85 % by weight of acrylonitrile units. The acrylic fabric has the ability to attract and convey moisture. Polyester is a synthetic polymer whose monomers are linked together by ester bonds. There are many types of polyester, but the term polyester commonly refers to a material made from polyethylene terephthalate. Polyester is highly flammable and tends to accumulate electric charge for a long time. Most synthetic fabrics have a natural ability to accumulate electric charge for a long time, because they are made from polymers. In addition to previously described fibers there

are many other kinds of naturals and organic synthetic polymers suitable for textile materials fabrication, such us triacetate, polyamide, elastane and other. There are also man-made inorganic fibers, such us metal, glass, carbon that can also be used for textile materials and fabrics [15]. Their use can essentially change the physical and electrical properties of the final products.

In practical applications, electrostatic properties of textile materials must be controlled.

Sample preparation. The investigated textiles were selected according to the short information on the data sheet provided by the manufacturer. The textiles treatment methods were not available for the authors; therefore, the following results obtained have only an indicative character. Textile test samples may appear in a variety of forms: they may be of different thickness, surface density and type of weaving; be of different composition, treatment method, softer or harder, and so on. But for the electrostatic properties measurement process it is important to know the moisture content of the fabric, because the moisture content substantially changes the measured data. Therefore, the measurements must be carried out in a controlled environment where the ambient temperature and the relative humidity must be specified. In order to cover the difference in relative humidity and moisture content of the fabric the test samples must be at least for a couple of hours in the specified environment conditions.

3.2. Comparative analysis of selected research materials

The experimental data reported here have been obtained when a small sample (51 mm × 46 mm) of textile material was affected with ion flux and electrostatic integral parameters were measured. The corona charging device voltage was $V_{cv} = 7.5$ kV and the time interval of the sample charging process – 5 ms. The measurement of surface voltage starts 35 ms after the sample charging process is finished and are measured at a 12 ms time frame. The measurement process was repeated every 200 ms. The measurements were carried out with seven different previously mentioned textile materials and were compared by limiting value V_{max}, maximum surface voltage semi-decay time t_{med} [s], deposited electric charge Q_{max} [mC·m^{-2}], sample capacitance C [nF·m^{-2}], accumulated electric charge energy W_Q [mJ·m^{-2}]. The textile materials samples were affected by negative (–) and positive (+) ion flux. All samples were subjected to the same conditions (see Table 1). Additionally in the Table 1 surface density [g·m^{-2}] and thickness [mm] of the investigated textile materials are presented. The data measured under the described conditions and presented in Table 1 suggest the following conclusions. The smallest surface voltage (about 90 V) is acquired by linen, the highest (about 2000 V) – by polyester coated with polytetrafluoroethylene. There is a group of textile materials that has good electrostatic performance because the surface voltage semi-decay time is about 1 s or less. The group is composed of linen, viscose, cotton and wool. The smallest surface voltage semi-decay time is for linen (about 0.1 s). The other group is composed of acetate, polyester and polyester coated with polytetrafluoroethylene, which have a significantly worse performance than the first group. The surface voltage semi-decay time of polyester coated with polytetrafluoroethylene is as large, as 60 s. The longer the semi-decay time t_{med}, the worse the antistatic ability of the textile material. The calculated value of a sample capacitance when the sample is affected by ion flux may differ from results obtained with other capacitance measuring methods, because the capacitance value depends on sample leakage current, electric field strength, electric charge polarization, measurement equipment frequency range and compression pressure, sample thickness and surface density, weather conditions and other. The numbers in parentheses in Table 1 were obtained by differential capacitance measurement of some investigated samples at mechanical pressure of 1.2 kPa and at frequency of 600 kHz without action of any external electric field. We can see some differences and similarities.

Table 1. Calculated parameters of selected textile materials when the voltage of corona charging device was $V_{cv} = 7.5$ kV, ambient temperature 23 °C and relative humidity 50 %

Textile materials		V_{max} / V	t_{med} / s	Q_{max}/mC·m^{-2}	C/nF·m^{-2}	$\lvert W_Q \rvert$ /mJ·m^{-2}	Surface density, g·m^{-2}	Thickness*, mm
Cotton	–	–1265.0	0.25	–0.57	39.3	31.44	264.0	0.96
	+	1001.0	0.28	0.59	32.0	16.03		
Linen	–	–92.9	0.10	–1.27	896.0 (27.8)	3.87	192.0	0.46
	+	91.3	0.11	1.73	825.0	3.44		
Wool	–	–1782.0	0.77	–0.37	20.8	33.03	332.5	1.11
	+	1527.0	1.34	0.71	10.8	12.59		
Viscose	–	–519.0	0.15	–0.65	132.0 (138.8)	17.78	75.8	0.13
	+	497.0	0.14	0.36	103.0	12.72		
Acetate	–	–1592.6	24.80	–3.31	43.5	55.17	114.9	0.21
	+	1705.0	30.90	2.82	22.4	32.56		
Polyester	–	–726.0	13.28	–4.33	258.0	67.99	51.3	0.10
	+	751.0	12.50	2.69	222.0	62.60		
Polyester coated with polytetrafluoroethylene	–	–2385.0	59.60	–0.36	14.9 (24.9)	42.38	176.6	0.53
	+	1989.0	60.40	0.12	8.67	17.15		

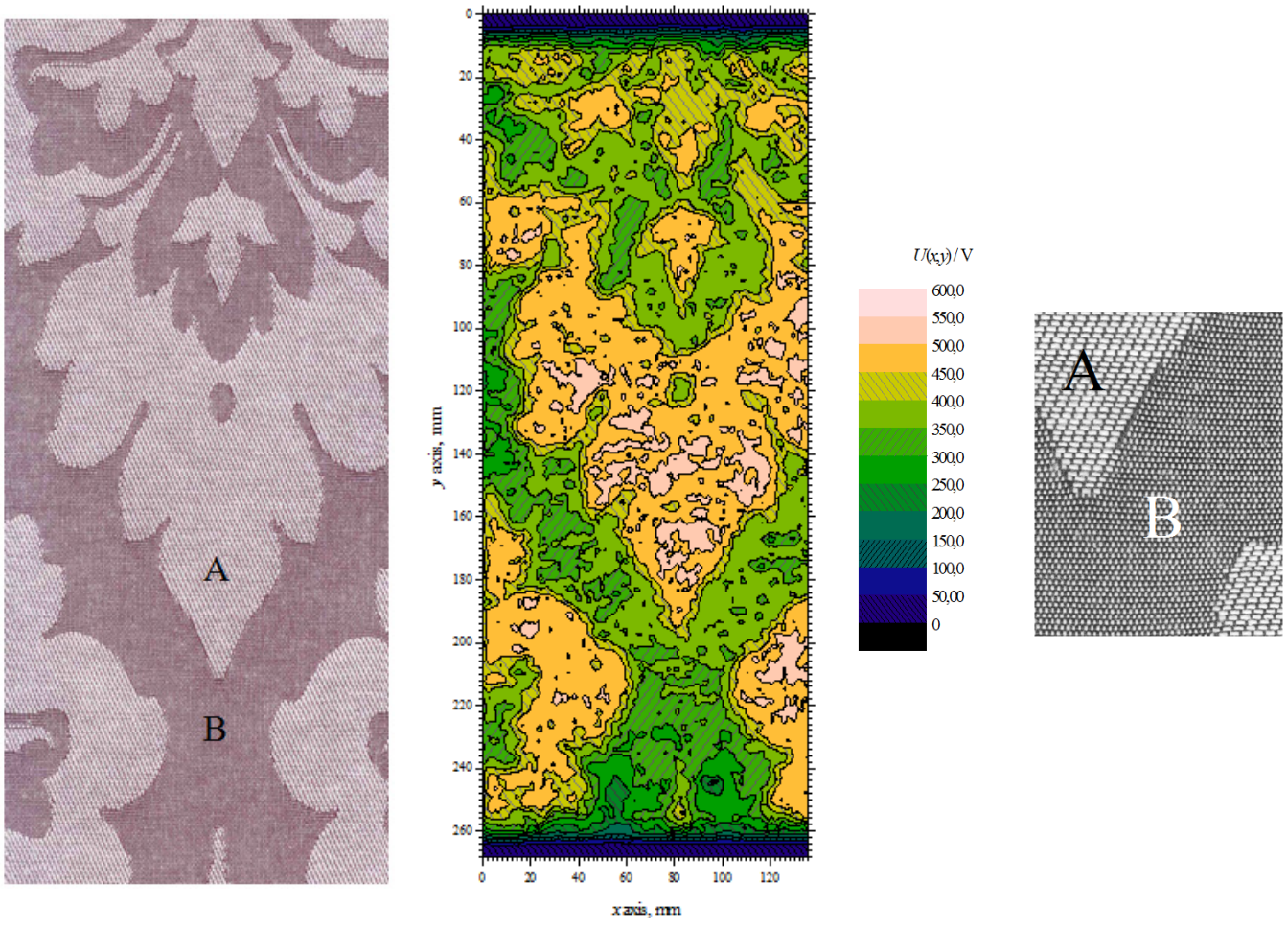
* The thickness was measured when the sample was pressed at a pressure of 1.2 kPa.

According to our research, performed with the measuring equipment produced in accordance with the standards described in [4, 5] linen is characterized by a certain surface and volume resistance, therefore the calculated capacitance when the sample is affected by ion flux is much larger than the measured differential capacitance at described conditions. In the case of viscose, capacitance values coincide quite well, because the surface and volume resistance is larger (about 10^4 times) than linen and the thickness variation at compression pressure is only 0.1 μm·kPa^{-1}. Polyester coated with polytetrafluoro-ethylene has the surface and volume resistance about 10^{15} Ω and the thickness variation at compression pressure is about 2 μm·kPa^{-1}, therefore the calculated capacitance when the sample is affected by ion flux is less than the measured differential capacitance. Also we can see that the largest accumulated electric charge energy is in polyester.

3.3. Surface voltage distribution of an upholstery fabric

The experimental data reported below are obtained when a sample of textile material (the sample dimensions are 250 mm × 210 mm) was affected locally by ion flux and a surface voltage distribution was measured as described in section 2.2. This measuring method takes the surface voltage of a small area spatially limited by voltage meter sensor dimensions. Such measuring method makes it possible to visualize the surface voltage distribution. An example of the measured surface voltage distribution is shown in Fig. 6. The sample was an upholstery fabric produced by "Audėjas" company, article name Fausta-1, composed by 66 % of cotton and 34 % of polyester. In Fig. 6, a and c, the brighter shade corresponds to cotton yarn and the darker shade correspond to polyester yarn. This is a weft double knit fabric in which a Jacquard type mechanism is used.

The experiment was performed at ambient temperature 23 °C and relative humidity 24 %, the corona charging device voltage +5.0 kV. The surface voltage was measured at 0.14 s after the ion flux treatment. In the Fig. 6, b, we can see zones with different surface voltages that vary from a very small value (about 50 V) up to about 600 V. The surface voltage value depends on the resulting arrangement of the fabric near the surface potential measuring probe. In the zone A (Fig. 6, a), the aluminum cylinder conductive substrate is covered by a polyester-cotton woven layer, which is coated by a layer of cotton using the Jacquard mechanism. In this zone surface voltage varies from 450 V up to 550 V. In the zone B, where the aluminum cylinder conductive substrate is only covered with a polyester-cotton plain woven layer, surface voltage varies from 150 V to 350 V.



a b c

Fig. 6. An example ofb ca measured surface voltage distribution: a – view of an upholstery fabric Fausta-1, b – surface voltage distribution, c – increased view of zones A and B

As it can be seen in Table 1, the cotton and the polyester maximum surface voltages V_{max} are more or less similar, but in the investigated upholstery fabric there are zones corresponding to two different cotton and polyester yarn weaving method, surface voltage values become different. To explain the results obtained, a deep examination of the physical phenomena of the measured structure is needed, but that is not the aim of this article. The presented example highlights the method of surface voltage distribution measurement that is well suited for quantitative analysis of textile materials' surface voltage and makes it possible to localize zones where electric charge is accumulated.

4. CONCLUSIONS

The results of the analysis lead to the following conclusions. A contact-free method and the measurement technique for electrostatic properties characterization of textile materials when they are affected by ion flux is suitable for testing of textile materials. This method takes it possible to measure main electrostatic parameters of textile materials, i. e. the maximum surface voltage, the semi-decay time, the deposited electric charge and a surface voltage distribution. The last mentioned parameter is a new parameter introduced to describe the electrical properties of textile materials. The performed experiments with different kinds of textile materials clearly show that the obtained data are inherent characteristics reflecting the electrostatic properties of textile materials. There are many factors that can affect the measured data: the composition of the fibers and yarns, the weaving mode, the compactness of the fabric, the production equipment and the process of treatment of the finally produced textile material, the atmospheric conditions (temperature, pressure and humidity), and the state of stress, the surface defects and many others. For deep understanding of the effects that take place in the investigated sample, the relationships between the properties of the investigated sample and the given measuring data and the factors that can affect the measured data must be known. We believe that the results will be useful for interpretation of experimental data and characterization of textile materials and allow manufacturers or designers to find a way to compare different materials as well as to use the method as a quality control test.

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