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Pressure-Potential Conversion in a Textile-Rigid Dielectric System

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Abstract

Results of the investigation of a double layer dielectric system consisting of textile and rigid dielectric layers is discussed in this paper. It is shown that the double-layer system submitted to an external stress produces an electrical potential distribution due to the trybo-charge generated during contact between the rough surface of an elastic-textile and the rigid dielectric layers. It is shown that the local effective surface charge density on the rigid dielectric layer depends on the intensity of the local stress - local pressure value. The charge generated produces proportional voltage on the solid dielectric layer after removing the elastic (textile) one. This way the pressure may be converted into a voltage signal, which is „memorised" by the solid dielectric layer. The "pressure map" converted into an „electric potential map" can be visualised by potential distribution determination. Potential distributions obtained for systems made of different materials (textiles) are presented in the paper.

Key words: *fabric, non-woven, electrostatic processes, electrets, transducers.*

Introduction

Contact electrification belongs to the earliest methods of solid material electrification that have been studied [1, 2].

It is difficult to realise uniform physical contact between the solid bodies along their surfaces, which finally results in non-uniform distribution of the charge generated on the surfaces after the finish of the electrification process. Relatively, physically uniform contact may be achieved only in such cases where one of the contact materials exhibits high elasticity (with a relatively low value of Young's modulus)

In the case of contact between the dielectric-conductor or dielectric-dielectric systems, one can expect additional phenomena associated with a relatively long relaxation time for the charge deposited on the surface (or injected into the volume) of the dielectric element. A long charge relaxation time results from both the low concentration of free charge carriers (long Maxwell's time constant) in the dielectric materials as well as from the low mobility of charge carriers injected into the dielectric (volume or surface) during the electrification process. In the case of generally applied polymeric materials (sheets), the charge relaxation time may be hours (PA – polyamide), days (PS-polystyrene), years (PP – polypropylene) or hundreds of years, like PTFE (polytetrafluoroethylene).

The last phenomenon suggests that the distribution of the surface charge generated during the electrification process may be "memorised" within a time comparable with the relaxation time on the dielectric element [3, 4].

Surface density of the charge generated during contact electrification depends on many factors, including the electrical properties of materials in contact, the properties of surfaces and possible interface (interlayer), atmosphere, temperature, the dynamics of the process and many others. Because of the large number of different phenomena participating in the electrification process, resulting in its complexity, as well as serious problems forming a precise description of the electrification process in practical situations, there is no one general model of the process proposed [5].

In any case, regardless of the direct physical mechanism responsible for contact charge generation in a particular experimental situation, the total charge generated on the surface of the object investigated depends on the real area of the bodies in contact.

Because of the finite values of the elasticity coefficient and smoothness of contact

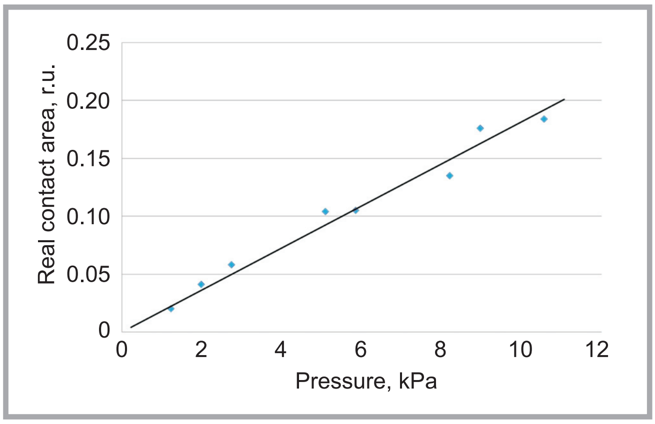

***Figure 1.** Dependence of the real contact area (relative units) for polypropylene woven fabric on the macroscopic pressure p_M applied perpendicularly to the interface. Estimated value of elasticity coefficient Y_1 = 55 kPa. (Real contact area estimated using Ink Calculator, ver. 3).*

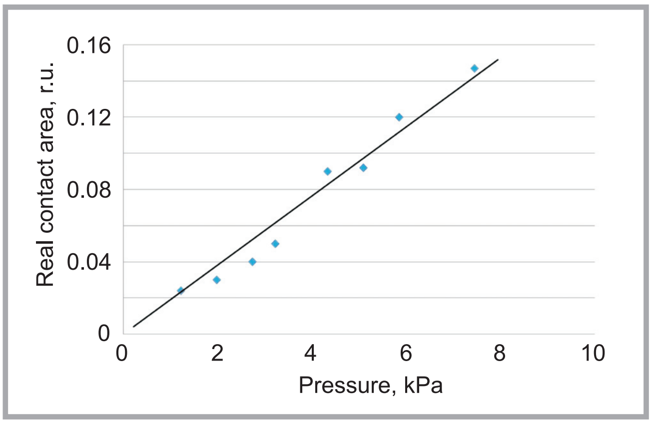

***Figure 2.** Dependence of the real contact area (relative units) for polypropylene non-woven fabric on macroscopic pressure p_M applied perpendicularly to the interface. Estimated value of elasticity coefficient Y_1 = 33 kPa. (Real contact area estimated using Ink Calculator, ver. 3).*

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surfaces, one can expect that the real contact area will depend on the macroscopic pressure p_M applied perpendicularly to the contact. In the case of a textile-rigid layer contact, the real contact area may be determined by plane metering the dark part of the white surface ”printed” by the textile layer, which is earlier painted and pressed to the base (rigid) layer with known pressure. Appropriate results of such measurements carried out for polypropylene woven and non-woven fabrics are shown in ***Figures 1*** and ***2*** (see page 71), respectively.

Results of measurements for the fabrics mentioned confirmed that the real contact area may depend (in the first approximation and for some of the stresses) almost linearly on the macroscopic pressure p_M applied to the whole system.

The above considerations were prerequisites for the theoretical model proposed and subsequent experimental investigations.

Pressure-voltage conversion

Let us consider a simplified model of an elastomeric ball made of material with an elasticity coefficient Y_1, pressed to the surface of a rigid base with a force resulting from the average (macroscopic) pressure p_M acting on the whole ball projection (on the interface-contact plane) surface S.

Under external stress the ball will be in close contact with the rigid surface over anarea s:

$$s = S\frac{p_M}{Y_1} \tag{1}$$

According to the definition, the average surface charge density q_S is determined by the relation:

$$q_s = \frac{Q}{S} = \frac{q_r s}{S} \tag{2}$$

where Q – is the value of the total charge generated by contact electrification on the ball surface – its projection on the interface plane S, q_r – surface charge density generated in the area of real contact s, resulting from direct contact between the layers. q_r depends on the physical properties of materials in contact and the particular electrification mechanism. Combining relations (1) and (2), one obtains:

$$q_s = \frac{q_r}{Y_1} p_M \tag{3}$$

The electrical charge of density q_s, on a one-sided metalised dielectric sheet of thickness d and relative electrical permittivity ε produces an equivalent voltage U, where:

$$U = q_r \frac{d}{\varepsilon\varepsilon_0 Y_1} p_M = A p_M \tag{4}$$

and

$$A = q_r \frac{d}{\varepsilon\varepsilon_0 Y_1} \tag{5}$$

is a constant, characterising conversion properties of the double layer system. The A constant is determined by the electrical and mechanical properties of particular layers, ε_0 – permittivity of a free space.

The simplified model described above highlights that the local value of the equivalent potential U (averaged over the projection area of one ball) depends linearly on the macroscopic pressure p_M. In reality the contact charge density q_r may also depend on the macroscopic pressure p_M . In consequence it will lead to the non linear dependence of $U(p_M)$. Additionally, the A constant may depend on x-y coordinates along the whole area of the double layer structure - transducer because of the non-uniformity of the layer materials.

Model of the structure

A model of the structure was constructed in the form of a sandwich, consisting of textile-elastic and rigid dielectric layers. A schematic section of the structure is shown in ***Figure 3***.

A 2.0 mm thick polymeric (polymethylmetacrylate - PMMA) plate was used as a solid dielectric layer, creating the base of the structure. One side of the base was covered with a conducting-graphite (or Al) layer. Before the experiment all the surface of the opposite side (non-metalized) of the base was discharged by tamponing it with ethanol. During the discharging of the base, the tampon holder was earthed. It was experimentally confirmed that the value of the residual potential measured before completing the structure did not exceed 200-300 mV. The elastic, converting layer was prepared from textiles made of natural (cotton) as well as polymeric (polyester– PET, polypropylene – PP, polyamide – PA and PAN - polyacrylonitryle) threads. The thickness of the elastic layer depended on the material used and was in the range of 85 to 900 μm.

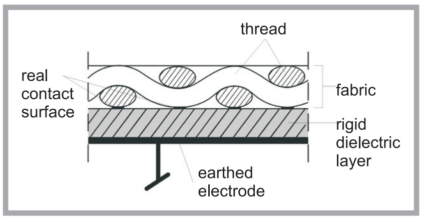

Figure 3. *Cross- section of the investigated structure.*

Approximate Young modulus values were estimated for the textiles investigated using relatively small stresses in the range of 30 – 110 kPa. During the experiment, the textile layer was placed along the discharged base and then submitted to an external stress applied perpendicularly to the surface of the base. After the application of the stress, the textile layer was softly removed, and the surface of the base potential was analysed. Rigid stainless-steel stamps, loaded with additional weights, were used for generating the stress applied to the structures and shaping the pressure map. Most of the measurements were performed using a stamp in form of a cylinder with a diameter of 12 mm.

Experiment

Measurements of the surface potential distribution were carried out in air in room conditions (T = 20 ± 2 °C, h = 62 ± 5%). The base was placed (its conducting side) on an earthed scanning table, equipped with a measuring head situated ca 1mm above the charged surface of the base. Surface potential measurements were carried out using a Trek Model 347 Electrostatic Voltmeter, which operates using the auto-compensation system and is equipped with a 6000B-15C end view measuring head. Because of the limited surface resolution of the head applied, the distance step during scanning was kept constant and equal to 1 mm for both directions of the analysis (axes). Surface potential measurements were performed ca 10 - 20 seconds after submitting the structure to the stress and at 1024 measuring points regularly distributed along the surface analyzed . The total analysis time and area were equal to 1024 sec and 20 × 20 mm, respectively.

The measurement data were collected, stored and converted using a standard PC, equipped with commonly used programs.

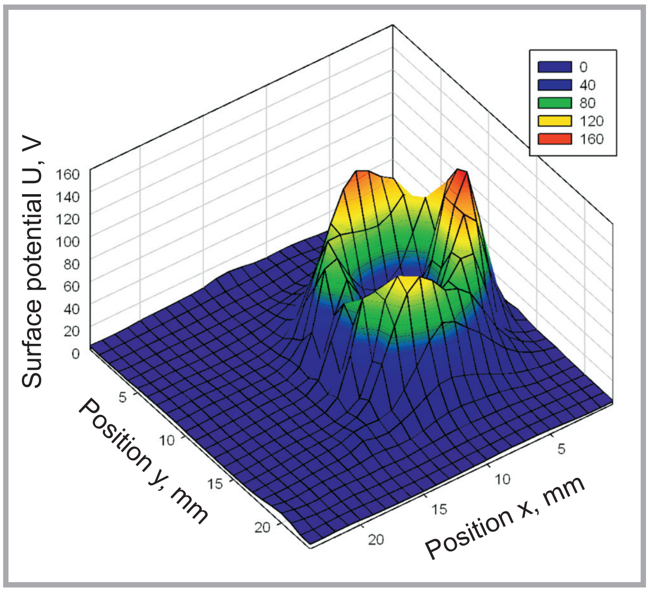

Figure 4. *Surface potential distribution measured on the PMMA plate after stressing the sandwich by a metal tube-like stamp with external and internal diameters 12 and 3 mm, respectively. Polyamide woven fabric with thickness 85 µm applied as an elastic layer. Applied pressure average value 6 kPa. Stress application time – 3 s.*

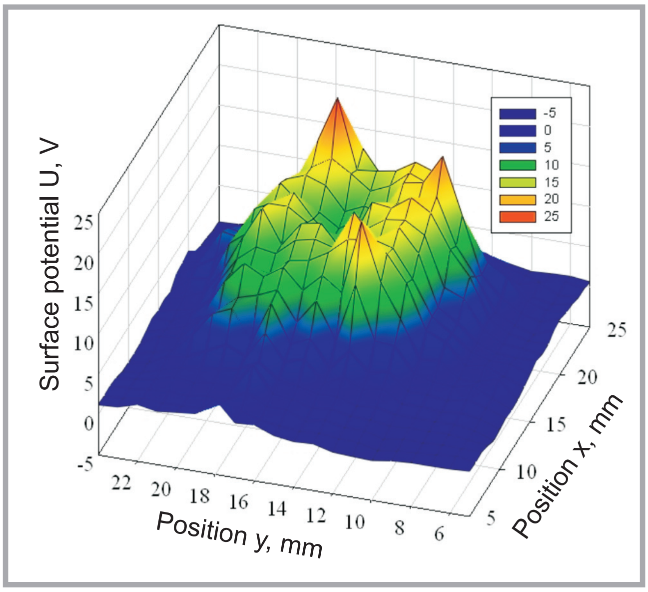

Figure 5. *Surface potential distribution measured on the PMMA plate after stressing the sandwich by a metal cylinder with diameter 12 mm. Polypropylene non-woven fabric applied as an elastic layer. Applied pressure average value 90 kPa (textile thickness ca 300 µm). Stress application time – 3 s.*

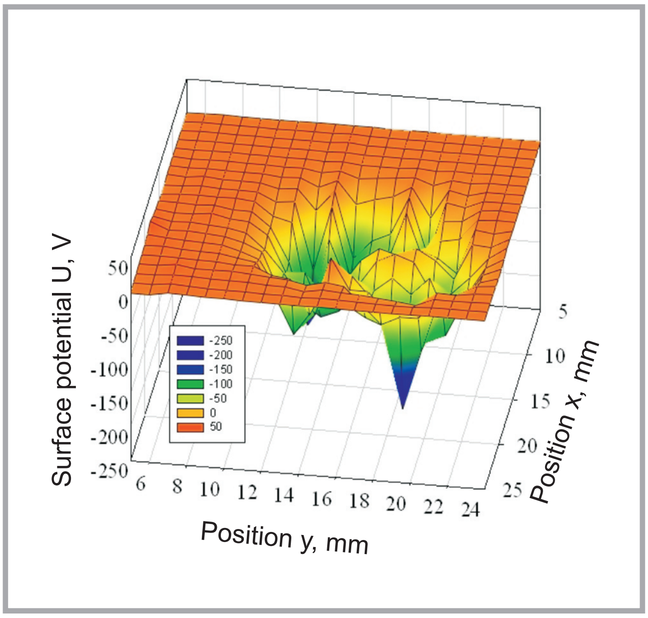

Figure 6. *Surface potential distribution measured on the PMMA plate after stressing the sandwich by a metal cylinder with diameter 12 mm. Cotton woven fabric applied as an elastic layer. Applied pressure average value 90 kPa (textile thickness ca 450 µm). Stress application time – 3 s.*

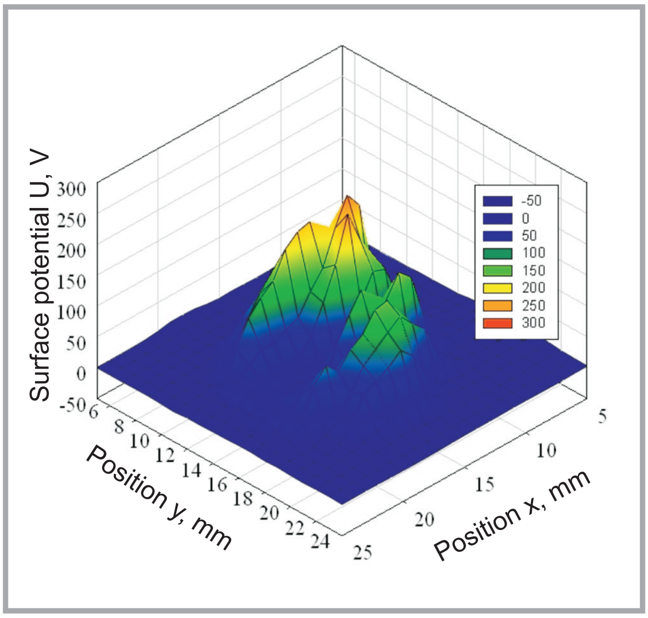

Figure 7. *Surface potential distribution measured on the PMMA plate after stressing the sandwich by a metal cylinder with diameter 12 mm. Polyamide-polyester woven fabric applied as an elastic layer. Applied pressure average value 90 kPa (textile thickness ca 250 µm). Stress application time – 3 s.*

Before the measurements, all of the textile samples of were washed. The washing process included washing in 0.4% (volume) water solution of a surfactant (Rokafenol®) for 15 min, carried out in a ultrasound washing bath, rinsing in tap water for 15 min, followed by rinsing in distilled water for 15 min. The samples washed were dried for at least 48 h in air, in conditions given above.

Results

Results of the surface potential distribution measured for the static (for a duration of a few seconds) stresses applied are shown for different textiles in ***Figures 4*** to *7*.

The results obtained for textiles made of polyamide and polypropylene threads, shown in ***Figures 4*** and ***5***, confirm that the pressure distribution may be successfully converted into potential distribution. Results shown in ***Figures 6*** and ***7*** were obtained for fabrics made of cotton and polyamide-polyester thread combinations, respectively.

The irregularities observed in surface potential distributions were due to a non-controlled transient pressure increase when the stressing stamp was placed on the structure. The "memorising" property

Table 1. *Surface potential values generated on the PMMA base by the textile layers submitted to the external stress (average value) of 90 kPa; *PAN (polyacrylonitryle) threads covered with electrically high conducting layer. (fabric) = (woven fabric).*

No	Threads	Surface potential maximum value, V	Surface potential average value, V	Textile thickness (stress 90 kPa), μm
1	PAN* (fabric)	500	200	350
2	Cotton (fabric)	200 (-)	100 (-)	450
3	PA-PET (fabric)	100	80	300
4	PP-PP (fabric)	60	30	250
5	PA-PET (fabric)	250	100	250
6	PA-PET (fabric)	100	20	300
7	PA-PP (fabric)	70	40	300
8	PA-PP (fabric)	200	100	200
9	PP (non woven)	125	15	200
10	PP (non woven)	120	40	1300

of the dielectric base of the structure causes the maximum value of the pressure applied to be finally memorised. Maximum and average values of the surface potential generated on the PMMA base of the structures described in section 3, using different textile layers, were collected for comparison in ***Table 1***.

Results collected in ***Table 1*** confirm that all of the textiles investigated may generate a surface charge on the dielectric base from PMMA. It is also seen that fabrics containing fibers made of the same basic polymer (formally) may generate a charge of various densities. This is probably due to the fact that the q_r parameter (see expression 5) is extremely sensitive to the surface properties of particular fibres in contact with the base material.

Conclusions

Results of the measurements of the surface potential distribution obtained for the structures desribed allow to draw the following conclusions:

- the true contact area between the textile and solid rigid layers may depend almost linearly on the pressure applied, especially in the range of relatively small stresses (i.e. for stresses lower than 100 kPa);
- a textile layer may be applied as the pressure-voltage “converting” layer;
- the phenomenon described appears in structures using different types of textiles, i.e. woven and non-woven, made of natural and synthetic fibres, conducting and non-conducting (electrically);
- in spite of the fact that the linear dependence between the pressure and surface potential (as predicted by the model proposed) was not confirmed experimentally , the results obtained highlight the fact that a textile layer may be applied to ‘convert’ pressure-voltage;
- surface potential (and pressure) distributions can be read-out or analysed for a relatively long time (hours) after submitting the structure to an external stress – with the possible application of typical electrostatic voltmeters;
- the simplicity of the mechanism desrcibed creates the possibility of preparing large transducers, whose surface may be analysed at the resolution and velocity required;
- the transducer pressure range and surface resolution could be easily tailored by applying materials exhibiting suitable electrical and mechanical properties;
- objects appearing in the contemporary human environment are frequently made of materials with a long charge relaxation time (thermoplastics). One can expect that pressure distributions could be memorised (in the form of potential distributions) for such elements subjected earlier to different external stresses for a relatively long time. The phenomenon described could be a basis for the preparation of a new investigation method in criminology (e.g. analysis of electrical “traces” left by a hand or even gloved hand on the surface of non-conducting objects).

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