Research Article

Ewa Korzeniewska*, Artur Szczesny, Andrzej Krawczyk, Piotr Murawski, Józef Mróz, and Sebastian Seme

Temperature distribution around thin electroconductive layers created on composite textile substrates

https://doi.org/10.1515/phys-2018-0007
Received Nov 01, 2017; accepted Nov 30, 2017

Abstract: In this paper, the authors describe the distribution of temperatures around electroconductive pathways created by a physical vacuum deposition process on flexible textile substrates used in elastic electronics and textronics. Cordura material was chosen as the substrate. Silver with 99.99% purity was used as the deposited metal. This research was based on thermographic photographs of the produced samples. Analysis of the temperature field around the electroconductive layer was carried out using Image ThermaBase EU software. The analysis of the temperature distribution highlights the software's usefulness in determining the homogeneity of the created metal layer. Higher local temperatures and non-uniform distributions at the same time can negatively influence the work of the textronic system.

Keywords: PVD process, thermograhs, smart textiles, computer analysis, thin layers

PACS: 44.90.+c, 73.61.-r, 73.90.+f, 85.40.Sz

***Corresponding Author: Ewa Korzeniewska:** Institute of Electrical Engineering Systems Lodz University of Technology, Lodz, Poland; Email: ewa.korzeniewska@p.lodz.pl
Artur Szczesny: Institute of Electrical Engineering Systems Lodz University of Technology, Lodz, Poland;
Email: artur.szczesny@p.lodz.pl
Andrzej Krawczyk: Faculty of Electrical Engineering Czestochowa University of Technology, Czestochowa, Poland; Military Institute of Medicine, Department of Teleinformatics, Warszawa, Poland;
Email: ankra.new@gmail.com
Piotr Murawski: Military Institute of Medicine, Department of Teleinformatics, Warszawa, Poland; Email: pmurawski@wim.mil.pl
Józef Mróz: Military Institute of Medicine, Department of Teleinformatics, Warszawa, Poland; Email: jmroz@wim.mil.pl
Sebastian Seme: University of Maribor, Faculty of Energy Technology, Maribor, Slovenia; Email: sebastijan.seme@um.si

1 Introduction

Elastic electronics, or textronics, rely on even current distribution to function effectively. The current must be evenly distributed throughout the entire surface element of the textronic system, as in the case of sensors [1, 2]. Temperature and temperature differences can affect the way the element works. Distortions to the current may result in the formation of hot spots or a decrease in the efficiency of the system [3, 4]. As in other areas of science, when designing an electronic systems on flexible substrates, optimization should be sought [5–7]. It is also important to take into account construction solutions in which the formed passive components do not adversely affect other nearby system components by their heating. It is important that the elements should not change their electrophysical properties through their own heating beyond the acceptable range.

The analysis of temperature distribution in circuits where temperature has a key influence on their functioning [8, 9], as well as in the vicinity of electrical-conductive paths, allows for proper selection of optimal working conditions for created systems. Such analysis allows for proper calculation of the heat balance of the electronic system. High temperatures cause changes in electrophysical properties of the systems by reducing the ampacity of conductive materials and gradually deteriorating the properties of the insulating materials. Thermal tests allow evaluation of the effectiveness of the adopted construction solutions. By using a temperature field analysis around the textronics or elastic electronic components, critical points of the electronic system may be indicated. They are spots or areas susceptible to damage or potentially introducing disturbances to the system.

Thermography as a non-invasive method of surface quality evaluation can be used in different fields of engineering *i.e.* for detecting surface cracks in welds [10, 11] or in concrete structures [12], identifying defects [13–15], determining the quality of ceramics [16], and also in medicine [17]. From this point of view, the analysis of temperature distribution is important for the application of thin-layer electronic structures in medical applications.

2 Experimental set

The temperature distribution analysis was carried out taking into consideration the electroconductive paths created on a flexible composite substrate, Cordura. Cordura is a textile material made of nylon threads coated on one side with polyurethane foil. The surface mass of this material is 195 g/m^2. Due to its high resistance to mechanical damage, Cordura is used to make products in which these qualities are of great importance, for example in sports shoes or military clothing.

The electroconductive path structures were produced using a PVD vacuum deposition process; silver with 99.99% purity was used as the deposited metal and was evaporated from tungsten boats. The thickness of the deposited layer measured in the indirect method was about 250 nm. Test samples of 50 mm in length and 3 mm in width were prepared. The geometrical structure of the created samples is shown in Figure 1. The current source was connected to the external current electrodes. Internal voltage electrodes were used to measure the voltage drop and finally to determine the resistance of the sample with a four-probe method [18]; in these cases the resistance equaled less than 1 Ω.

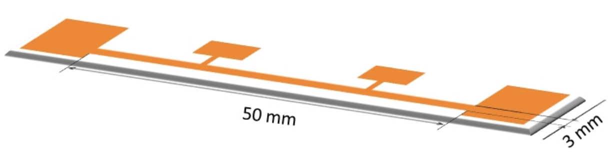


Figure 1: Geometry and dimensions of the test structure created in PVD process on textile substrates

The tested samples were connected to a DC source with a set output value of 200mA. The ambient temperature was 23°C. After a set time of 10 minutes, when the temperature of the sample was stabilized, images were taken using a FLIR T650sc thermal camera. The analysis of the thermographs was made on the basis of Image ThermaBase EU software developed by authors for temperature distribution analysis [19]. The program is used to acquire, process and collect thermographs obtained during measurements with thermal imaging cameras. The software was based on Power Designer 7.5 CASE and RAD / Delphi from Borland Delphi 5. Sybase SQL Anywhere 6 was used as a database engine.

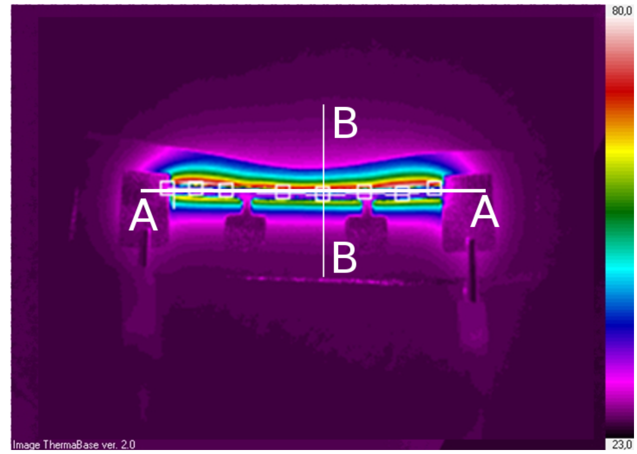


Figure 2: The thermograph of the electroconductive thin-film structure. (Temperatures measured in °C

3 Results of experiments

An exemplary thermograph of a thin-layer structure and space around the electroconductive layer is shown in Figure 2.

Figure 3 shows the spatial temperature distribution around the created silver layer connected to the current source at the time of reaching the stable temperature of the entire system.

The temperature distribution along the line through the central part of the electroconductive element (shown in Figure 2 as the cross section A-A) is shown in Figure 4a, and along line B-B is shown in Figure 4b. The A-A line was divided into 150 measurement points and the B-B line into 47 measurement points. The temperature of the structure was determined at each of these points and the collected data are presented in Figure 4. The analysis of the graphs allows estimation of the linear temperature distribution on the surface along and across the electroconductive path.

The graph analysis (Figure 4a) shows that the temperature changes from about 30°C to 41°C along the layer, and the local temperature increase is most likely due to inhomogeneity of the thin structure created in the vacuum deposition process or the unevenness of the substrate. The microscopic image of the composite material which was used as the surface is shown in Figure 5. This image was made with 1500x magnification using a SEM Hitachi S-4200 electronic scanning microscope.

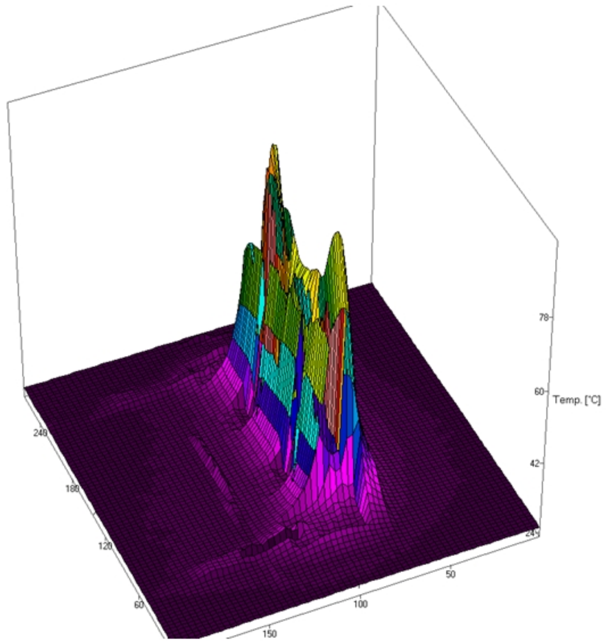


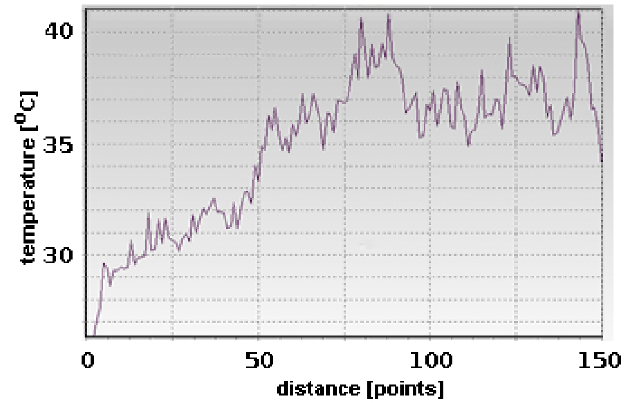
Figure 3: The spatial temperature distribution in the area around the formed thin layer structure

The features described above cause differences in the recorded temperatures measured along one line (*e.g.* line A-A in Figure 2), where the current density should be nearly uniform. It is impossible to obtain exact information about the temperature distribution only by analysing the thermographs and observing differences in colours. The Image ThermaBase EU software with temperature field analysis is helpful during this kind of study.

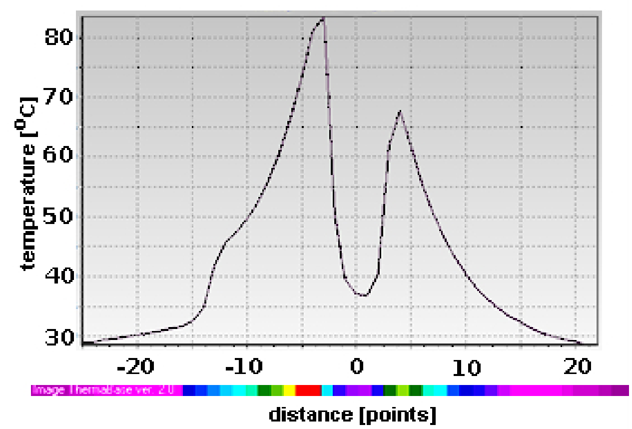
Figure 4b shows the temperature distribution across the analyzed structure (line B-B in Figure 2) taking into account the area in the nearest neighborhood of the examined layer. The graph shows that the area near the electroconductive layer is the most heated, and the temperature there is up to 80°C, while the average surface temperature of the metallic layer does not exceed 40°C.

This is the effect of heat dissipation from the top layer of the heating structure. The differences in warming are influenced by a number of factors, such as the flow of air around the analyzed structure caused by both forced and natural convection, and the phenomena of conduction and heat radiation. For a circuit with more complex geometric arrangements, where a large number of electronic components are accumulated on a small area, similar temperature field analysis is recommended because of the local overheating and additive character of the generated heat.

Image made with the scanning electron microscope (magnification 1500x).



(a)



(b)

Figure 4: Graph of the temperature distributions a) along and b) across the thin layer sample

Analysis of the temperature distribution over the metal surface can help to determine the quality of the created layer. Greater irregularity in the temperature distribution indicates a greater number of structural defects in the metallic coating. Due to introduced disturbances in the transport of electrical charges, such defects have a significant influence on the amount of heat generated and transported in the structure.

The temperature distribution, in the form of isotherms and temperature gradients, is presented in Figure 6. These graphs show the distribution of heat in the composite substrate.

The temperature distribution, which is shown in the form of isotherms in Figure 6, shows that the substrate is heated evenly by heat dissipation from the metallic structure. This confirms the role of the substrate in the heat

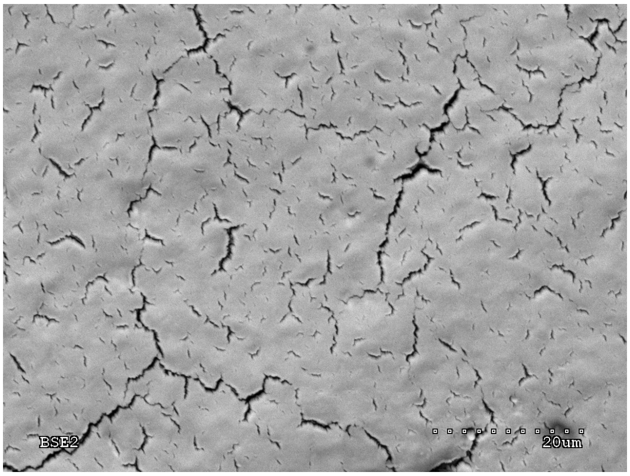
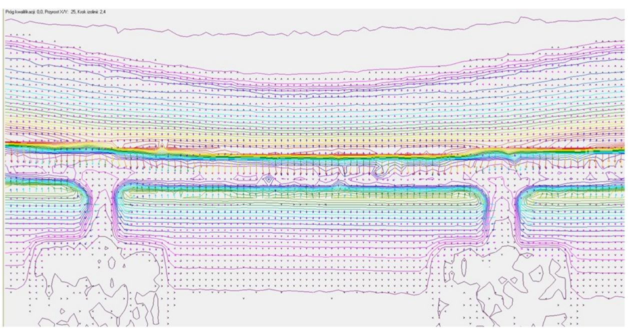
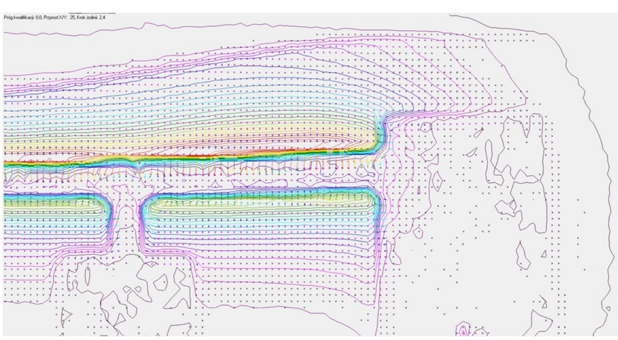


Figure 5: A microscope image of the Ag layer deposited on a Cordura composite material substrate



(a)



(b)

Figure 6: Gradients of temperature and isotherms in the area around a) the electroconductive path b) around the current electrode

transfer process. Cordura, made of two polymeric layers, has a thickness of about 500 μm, and its heat capacity is much higher than that of the applied metal. This has an effect on the uniform distribution of temperature around the resulting metallic structure.

The electroconductive path formed on the polyamide-polyurethane layer in the upper part of the Cordura is cooled by passing heat to the surrounding air, while cooling in the lower part occurs by transmission of heat to the substrate. Because of the significant differences in the thermal conductivity of silver (419 W/K·m) [20], polyurethane (0.035 W/K·m) and air (0.025 W/K·m) [21, 22], cooling of the metallic layer is much faster than the heat transfer from the polyurethane substrate. Propagation of heat occurs radically and evenly from the electroconductive path. No excessive heating of the current electrodes is observed (Figure 6b). Analysis of thermographs can also help in detection of structure defects.

4 Conclusion

The paper presents the results of an analysis of temperature distribution around electroconductive metal paths created by a PVD process on a composite textile substrate. From surface analysis of temperature distribution, arming occurs due to heat conduction from a thin metal layer as the result of the different conductivity values of the substrate, the applied metal and the air heat capacity.

In the observed thermographs, heterogeneities in emissions and heat transfer can be observed. The differences in heat dissipation are the result of lots of microcracks in the metallic layer. Because of non-uniform heating, the structure may be susceptible to damage as a result of its local overheating, which can consequently cause accelerated aging of components made on the basis of such layers. For medical applications it is important to take into account the fact that heterogeneity of heat emission can lead to micro burns, so the maximum temperature values on the surface of the layer should be considered. Because the heat emission will have to be limited by the maximum temperature values, the total efficiency will be lower than would be expected from a more homogeneous structure. Such structures create opportunities which are difficult to achieve by other methods, but it is also advisable to continue work to improve the quality of structures because of the need to improve homogeneous heating.

Due to the good heat dissipation from the substrate causing a rapid drop in temperature, the structures made on the Cordura substrate can be used in applications where a precisely located heat source is required [23]. Textronics elements can be created close together on this type of substrate, without heating each other. The presented textronic structures can also be used in any application requiring precise and complex heating structures such as electronic components.

References

[1] Frydrysiak M., Korzeniewska E., Tęsiorowski Ł., The textile resistive humidity sensor manufacturing via (PVD) sputtering method, Sensor Letters, 2015, 13, 998-1001.

[2] Stempien Z., Kozicki M., Pawlak R., Korzeniewska E., Owczarek G., Poscik A., Sajna D., Ammonia gas sensors ink-jet printed on textile substrates, Proceedings of IEEE Sensors 2016, 2017, 7808457

[3] Banaszczyk J, De Mey G., Schwarz A., Van Langenhove L., Current Distribution Modelling in Electroconductive Fabrics Fibres & Textiles in Eastern Europe 2009, 73

[4] Rakotoniaina J.P., Breitenstein O., Langenkamp M., Localization of weak heat sources in electronic devices using highly sensitive lock-in thermography Materials Science and Engineering, 2002, B91-92, 481-485.

[5] Kasprzyk L., Tomczewski A., Bednarek K., The distribution of an electromagnetic and optimization computation of electrical systems by using multi-core processors, Przeglad Elektrotechniczny, 2011, 87, 82-85.

[6] Kasprzyk L., Bednarek K., Speeding up of electromagnetic and optimization calculations by the use of the parallel algorithms, Przeglad Elektrotechniczny, 2009, 85, 65-68.

[7] Pawlak R., Rosowski A., Tomczyk M., Walczak M., Laser microscale technologies: modeling assisted processes, Proc. SPIE 8703, Laser Technology 2012: Applications of Lasers, 87030N 2013, DOI:10.1117/12.2014979

[8] Lebioda, M., Rymaszewski, J., Korzeniewska, E. Simulation of thermal processes in superconducting pancake coils cooled by GM cryocooler, Journal of Physics: Conference Series, 2014, 494, 012018

[9] Rymaszewski J., Lebioda M., Korzeniewska E., Simulation of the loss of superconductivity in a three-dimensional model of the metal-superconductor connection, Przeglad Elektrotechniczny 2012, 88, 183-186.

[10] Broberg P., Surface crack detection in welds using thermography, NDT&E International, 2013, 57, 69-73.

[11] Świątczak T., Tomczyk M., Więcek B., Pawlak R., Olbrycht R., Defect detection in wire welded joints using thermography investigations, Materials Science and Engineering B, 2012, 177, 1239-1242.

[12] Milovanović B., Banjad Pečur I., Štirmer N., The methodology for defect quantification in concrete using IR-thermography, J. of Civ. Eng. and Manag., 2017, 23: 573-582.

[13] Korzeniewska, E. Murawski, P. Krawczyk, A. Pawlak, R., Defect detection in electroconductive thin layers via thermography method, Przegląd Elektrotechniczny, 2016, 1, 93-95.

[14] Ibarra-Castanedo C., Gonzalez D., Klein M., Pilla M., Vallerand S., Maldague X., Infrared image processing and data analysis, Infrared Physics & Technology 2004, 46, 75-83.

[15] Abdoulahad T., Modeling and optimization of open crack detection by flying spot thermography, NDT & E International 2017, 89

[16] Sfarra S., Perilli S., Paoletti D., Ambrosini D., Ceramics and defects Infrared thermography and numerical simulations - a wide ranging view for quantitative analysis; Journal of Thermal Analysis and Calorimetry 2016, 123, 43-62.

[17] E.Y.-K. Ng, A review of thermography as promising non-invasive detection modality for breast tumor, Int. J. of Therm. Sci., 2009, 48 849-859.

[18] Korzeniewska E., Jakubas A., Measurement of surface resistance of thin layers of different shapes produced on flexible substrates (in Polish), Przeglad Elektrotechniczny, 2014, 12, 233-236.

[19] Murawski P., Jung A., Ring E.F.J., Zuber J., Plassmann P., Kalicki B., Image ThermaBase- A software programme to capture and analyse thermographic images, Thermology International 2003, 13, 5-10.

[20] Silver - online catalogue source, sources, small quantity and quantities from Goodfellow: http://www.goodfellow.com/E/Silver.html

[21] PN-EN ISO 12524:2003

[22] Korzeniewska E., Szczęsny A., Seme S., Krawczyk A., Murawski P., Mróz J., Analysis of the temperature field around the thin electroconductive layers formed on the substrates. Experimental and analysis results, IEEE Xplore Digital Library, 2017 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF) Book of Abstracts

[23] Pawlak R., Lebioda M., Tomczyk M., Rymaszewski J., Korzeniewska E., Walczak M., Surface heat sources on textile composites – Modeling and implementation IEEE Xplore Digital Library, 2017 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF) Book of Abstracts