

Polymer film strain gauges for measuring large elongations

A P Kondratov¹, A M Zueva¹, R S Varakin¹, I P Taranec¹ and I A Savenkova²

¹Moscow Polytechnic University, 107023 Moscow, Russia

²National Research University Higher School of Economics, 101000 Moscow, Russia

E-mail: apkrezerv@mail.ru

Abstract. The paper shows the possibility to print polymer strain gages, microstrip lines, coplanar waveguides, and other prints for avionics using printing technology and equipment. The methods of screen and inkjet printing have been complemented by three new operations of preparing print films for application of an electrically conductive ink layer. Such additional operations make it possible to enhance the conductive ink layer adhesion to the film and to manufacture strain gages for measuring large elongations.

1. Introduction

Films and fibrous sheets with integrated electrical functions allow creating smart materials and structures with a variety of applications in aircraft engineering and avionics [1], special cloths for test pilots and aerodrome equipment operation safety systems. In the last decade, there has been an increased interest in printed electronics products: strain gages, microstrip lines and coplanar waveguides for microwave devices produced using roll-to-roll planar technology. [2] The most widely used methods are screen and inkjet printing methods using conductive ink and inks [2]. The inkjet method is a printing technology that has the advantage of productivity and variability, i.e. the possibility of a prompt change in the strain gauge shape and size. Most of the conductive inkjet inks contain water as a solvent [2]. Water features a high surface tension and viscosity, which does not allow for forming drops of the optimum size (30–100 µm) by the inkjet printing method [4]. For this reason, the task of developing alternative ways of applying ink and images on flexible polymer substrates, providing an optimal thickness of the conductive layer, remains very relevant. Other important tasks in the strain gage production are increasing interlayer adhesion, enhancing printed layer and substrate resistance to multiple cyclic deformations of large magnitude.

One way to increase the interlayer adhesion in printed images is shown in [5] the paper, that studies the process of applying insulating waterborne ink on the surface of a film resistor printed on a propylene film using the screen printing method. There is an experimental evidence for the effectiveness of screen printing method when applying ink on a “wet layer” of a conductive graphite-containing composition. The graphite-containing composition adhesion to the propylene substrate and waterborne ink adhesion to the conductive layer of a film resistor are rather low; therefore it is not advisable to use this method to manufacture strain gauges and large deformation sensors, resistant to cyclic stretching.



2. Main result

To manufacture strain gages capable of multiple significant stretching without breaking the interlayer adhesion to the polymeric substrate, it is possible to use the “dry crazing” effect of polymers in a state of rigid elasticity [6].

The crystal structure of rigid-elastic films becomes microporous and reversibly reconstructible when stretching and shrinking without plastic deformation. The film elastic deformation reversibility is manifested as a cyclic change in the film color in polarized light [7]. The film microporosity with reversible deformation reaches a maximum at a relative elongation of 20%.

The new way of printing strain gages on polymer films includes three additional operations to increase the adhesion of the conductive ink layer to the elastic substrate. The first operation is stretching and shrinking of the polymer film in a state of rigid elasticity in a gaseous environment (atmosphere). This forms an open pore structure. The second operation is re-stretching the film and fixing it in the stress-strain state in the printing press under a screen form. The third operation is an instant film shrinking after printing an ink layer. This stage involves the “capture” of the liquid ink by closing the substrate pores.

Electrical and mechanical features of strain gages produced using the new method are shown in Fig.1:

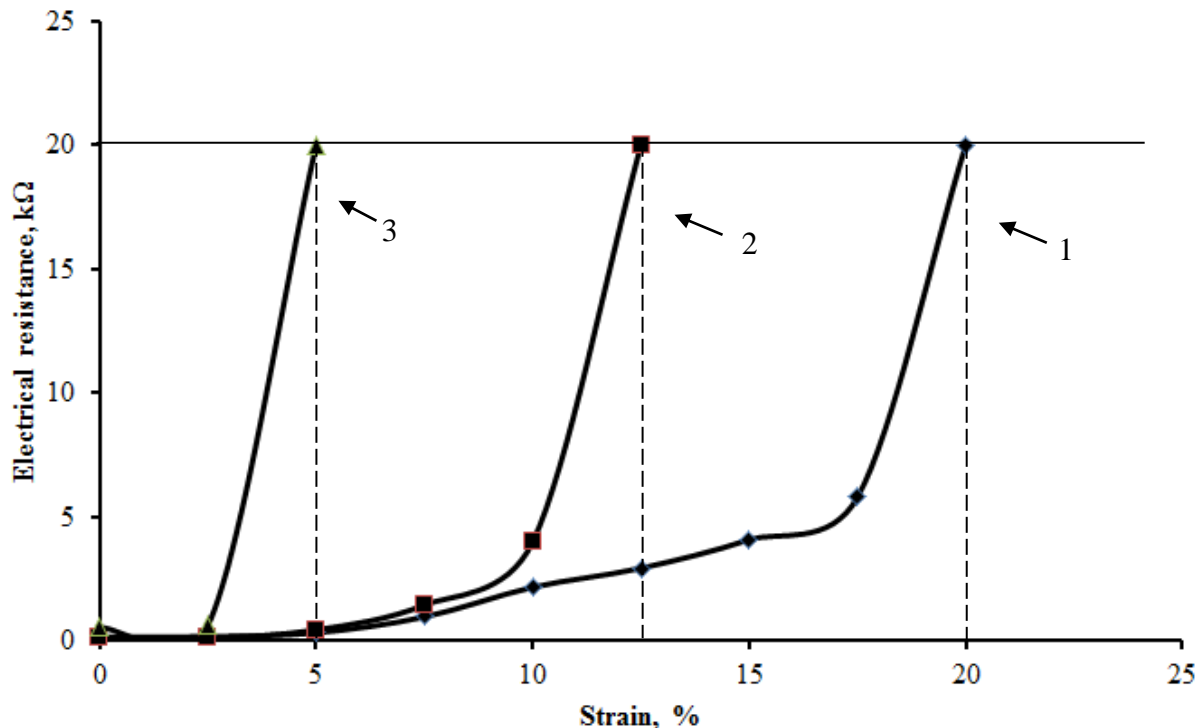


Figure 1. Resistance of strain gages prints obtained by screen printing. The thickness of the conductive ink layers (SunChemical Conductive Graphite 26-8203): 10 (1), 60 (2), 85 (3) μm .

The strain gauge electrical resistance depends on the ink layer thickness. The layer thickness is adjusted by choosing a printing form (screen line number) within a range of 10 to 85 μm . When the ink layer thickness is 10 μm , the linear strain measurement range with a strain sensitivity of 600 is 0 to 18%. When the ink layer thickness is 60 μm , the linear strain measurement range with a strain sensitivity of 1600 is 0 to 8%. When the ink layer thickness is 85 μm , the linear strain measurement range with a strain sensitivity of 700 is 0 to 3%. Strain gage prints with different ink layer thickness can be used as mechanical switches or open circuit sensors in electrical schemes, which are programmed to a certain resistance by choosing the ink layer thickness. The threshold resistance of 20 k Ω with different layer thicknesses is achieved at 5, 12, 20 % elongation. The new printing method

allows for manufacturing film strain gages and elastic strain gages of up to 70% and more. For this purpose, it is necessary to change the method of applying the conductive ink on a stress-strain film and to use conductive composition of lower viscosity.

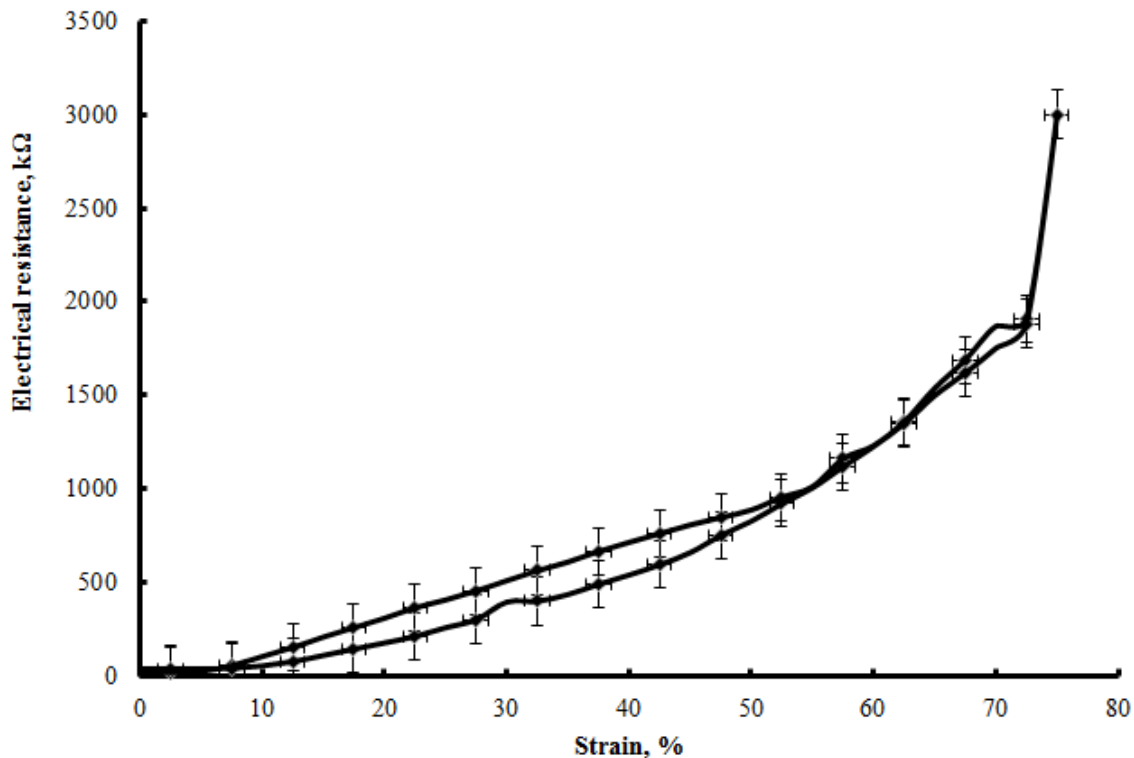


Figure 2. Resistivity of fingerprints of strain gages obtained by spraying a graphite spray (model Kontakt Chemie GRAPHIT 33) onto a film of rigid polypropylene at the time of extension by 70%. The thickness of the layer of electrically conductive ink is 5 μm .

Fig. 2 shows the strain sensitivity of the strain gage print manufactured by spraying a conductive composition spray onto a rigid polypropylene film using the suggested printing method. The measuring range of the relative tensile strain is 0 to 70%. The electrical resistivity dependence on the relative elongation is described with high reliability ($R^2=0.95$) by the following equation:

$$\Delta Q/Q_0 = G \cdot \epsilon^2 \text{ or, approximately, } (R^2=0.87) \quad \Delta Q/Q_0 \approx G \cdot \epsilon,$$

Where: Q is the strain gage electrical resistance (Ohm), G is strain sensitivity and ϵ is relative extension (%).

3. Conclusion

Different strain gauge resistance values at the moments of stretching and shrinking do not exceed the measurement error, provided that the relative deformation values are equal (40%). Resistance of these strain gage parameters to large cyclic deformations is due to the features of the polymer substrate structure and the mechanism for fixing the ink layer on the surface of a rigid polypropylene film. The polypropylene film deforms to form a plurality of nano- and micropore crazes [8], the highly developed surface of which is formed during the first operation of stretching the printed substrate in an air environment. The high specific energy of the new craze surface is lower due to adsorption of fluid molecules and ink ingredients. The instant film shrinking after it's contact with liquid ink allows for mechanically capturing the conductive dye particles and moving the same to the pore volume. After removing solvents and craze structure collapse upon reducing the film length [9], particles of the conductive dye, concentrated on its surfaces inside the film, come into contact and, due to multiple

contacts with each other, ensure a high electrical conductivity of a strain gage at large cyclic deformations.

References

- [1] Mishra A and Mishra D 2010 *An Exploratory Review. Promet – Traffic&Transportation* **22**(5) 363.
- [2] Stoppa M and Chiolerio A 2014 *Sensors* **14**(7) 11957.
- [3] Khairilhijra K, Tan S C and Khairul A M 2016 *Journal of Engineering and Applied Sciences* **11**(10) 6619.
- [4] Huang D and Liao F 2003 *Journal of the Electrochemical Society*, **150**(7) 412-417.
- [5] Kondratov A P, Zueva A M and Nagornova I V 2017 Parameters dynamics estimation method for printed electronics conductive elements layers 2017 *IEEE Dynamics of Systems, Mechanisms and Machines (Dynamics) (Omsk, Russia)*
- [6] Kondratov A P 2014 *Light & Engineering Svetotekhnika* **22**(3) 74.
- [7] Varepo L G, Ermakova I N, Nagornova I V and Kondratov A P 2017 *AIP Conference Proceedings* **1876** 020080
- [8] Rukhlya E G, Yarysheva L M, Volynskii A L and Bakeev N F 2016 *Physical Chemistry Chemical Physics* **18**(14) 9396
- [9] Trofimchuk E S, Efimov A V, Nikonorova N I, Volynskii A L, Bakeev N F, Nikitin L N, Khokhlov A R and Ozerina L A 2017 *Polymer science. Series A* **53**(7) 546