Tenso-resistive printed sensors for flexible elements of systems and mechanisms

A P Kondratov¹, I V Nagornova¹ and L G Varepo²
¹Moscow Polytechnic University, 38 B. Semenovskya str., Moscow 107023, Russia
²Omsk State Technical University, 11 Mira ave., Omsk, 644050, Russia

Abstract. The testing results of developed tenso-resistive (strain-gauge) sensors printed on 2 types of synthetic nonwovens, using 2 modified types of conductive inks based on carbon nanotubes, graphite, for such flexible high-load and stretchable elements as air-inflated structures, amortization groups and especially soft robotics systems and mechanism are presented. The strong correlation “stretch deformation range – electrical resistance – tenso-sensitivity” for each tested nonwovens was found. The sensors developed on synthetic nonwovens with nanotubes were defined to be most suitable for wider deformation control variety (0-80%) as well as humidity control with dividing on 3 narrow sensitive ranges from 0 to 10, 10-30 and 30-80% elongation. The affect of material density as well as prepress surface thermo-modification and environment conditions deviations was checked. The advantages of these sensors are low-cost and simple operation principle in contrast to other commercially available sensors or known prototypes. All of these sensors were produced using a screen-printing technique.

1. Introduction
Flexible sensors are applied for robotic-arm, damping control, pressure measurement in the wind flow environment, wearable electronics and etc due to their dynamic advantages over the rigid ones [1-7]. According to [1-4] the use of such sensors for artificial intelligence and robotics has been one of the primary applications of sensors in the industrial sector in the past few years, for example for real-time movement monitoring of robotic arms.

At present, the fabrication of flexible tactile sensors is generally based on electronics embedded in flexible polymeric materials, in particular, several research groups have embedded different conductive organic and inorganic elements on silanes, urethanes, rubber or silicones based elastomers [1-7]. One of their common disadvantages is forming of microcracks within the substrate even at low strains whereas skin linear elastic response up to tensile strains of 15% - so, these materials may be unsuitable for robotic-arm or wearable electronics applications [2, 7].

Among the different types of flexible sensors available in the market, flexiforce sensors are one of the prominent ones, due to their low cost and simple operating principle [1, 12]. One of the integrated sensor actuators developed in [1] is presented in fig.1. It should be noted that this sensor, based on mesh-like patterns (fig.2), works at different mechanical strains (ε = 2%, 5%, 10%) and low sheet resistance of ≈ 8 Ω sq⁻¹.
Others sensors examples based on metal nanoparticles as well as carbon nanotubes integrated into different material by physical methods are described in [12].

In our study we have used nonwovens as a suitable sensor substrate since for some robotic applications although at the moment such nonwovens application are slightly spread: in [9, 11] existing and potential applications for nanofibre nonwovens are presented, including energy and electronics, military, and bioengineering (figure 3). Nonwoven fabrics are broadly defined as sheet or web structures bonded together by entangling fibre or filaments (and by perforating films) mechanically, thermally or chemically. They are not made by weaving or knitting and do not require converting the fibres to yarn [10].

Deformation properties, structure as well as both nonwovens fiber crystallization and orientation were examined in [9, 10, 12, 13], including carbon nanotubes filled ones in the context of wearing electronics application.

Authors [12] had been noted that workability of strain sensors on nonwoven substrates (elongation variation of electrical resistance) has a feature – irreversible deformation after the first strain cycle, as
well as at the low and high strains (fig. 4). As exemplified by the strain-gauge sensor produced by CNT filtration through a nonwoven, after a cyclic strain a change in the robust composite films on the conductive networks caused slightly film damaging (cracking) into fragments when stretched was shown with fail-safety mode at the higher elongations. In our research we have used more efficient sensor production method namely screen printing ones to avoid both size and time limits.

Also it is well known porosity exerts a great influence over not only mechanical properties, but printing ones, it is important for wearing electronics items and robotic arms. So, screen printing procedures features on nonwovens using typical printing inks were presented in [21] and by conductive silver ones – in [24].

However, it should be noted that sensitivity and reliability are not the only factors to be considered in fabricating strain-gauge sensors, owing to the possibly complicated working environments, especially in raining days, or in moist conditions. Therefore, strain-gauge sensors with both high sensitivity and good water-repellency are important to electronic sensor devices [23] and electrical resistance constancy at the varied RH.

In the present work, we report a simple and economic method for the fabrication of a tenso-resistive sensitive to different range deformation sensor screen printed on nonwovens with 2 types modified inks.

2. Methods

As the sensors substrates were chosen 2 nonwovens types based on [16]

- polypropylene (PP) nonwoven “spunbond” type, density 60 gsm\(^{-1}\) - NWM-1
- needle-punched PP nonwoven, density 160 gsm\(^{-1}\) - NWM-2

At the earlier research [18,19] of ink penetration into porous nonwoven structure substrate thermo-modification necessity for ink loss decreasing and spreading improving was proved. So, for PP nonwovens and hydrophobous-based inks thermo-modification with organic solvents in a contact is reasonable. The treatment efficiency estimated by sorptive capacity of photopolimerizable compositions melts was also shown in [20].

The device for nonwovens structure bodying by heated roll pressure and at the same moment coating by liquid components (primers, antistatic agents, biocidal and antifungal mixtures and etc) aimed to storage biodeterioration avoiding was developed. Nonwovens were modified at 120°C for 1 min.

The sensors were screen printed on modified nonwovens as lines with 10 mm thickness using 120 lpi screen plate. Ink compositions based on single-wall nanotubes TUBALL™ COATOCSiA (CNT-ink) and also a commercially available screen conductive ink Sun Chemical contained both graphite and amorphous carbon (graphite ink), which were ultrasonicated in presence of polyoxyethylene glycol ether of higher fatty alcohols (OS-20) and non-ionic surfactant (OP-7) were developed. Aimed to viscosity control and conductive layer adhesion to a substrate improving either butyl acetate or polyurethane adhesive was added to used ink compositions. All chemicals were of laboratory grade. Samples were produced at 22±2°C and RH45-50%.

The used electrical measuring scheme in sensor deformation conditions in a d.c. and a.c. circuit (at 50Hz and 100 kHz) is presented in figure 5. Sensor samples resistance was calculated according to resistor voltage drop (5) controlling AC current amplitude by scope (2) at 1mA.
Deformation-strength properties of sensor samples were defined according to the National State Standard 15902.3–79. The deformation properties of initial, modified and printed samples were mechanically tested on each stage.

Strain gauge factor was calculated by variously deformed sample resistance measuring (at different elongation): a dependence graph (resistance as a function of tenso-resistive sensors deformation) was divided in straight areas, then the strain gauge factor was computed as (1)

\[ K = 100 \cdot (R_2 - R_1) \cdot \frac{1}{R_1} \cdot \frac{1}{(\epsilon_2 - \epsilon_1)}^{-1} \]  

Sensors resistance to RH environmental changes was estimated by samples aging for 1, 7 and 14 days in an exiccator by their above water placement at 90-95% RH accompanied with step-by-step electrical resistance without deformation.

3. The results

The maximum deformation values of used PP substrates produced by different technological techniques – by local thermally-bonding and needle-punching [17] - are presented in table 1.

As it shown in table 1, the NWM-1 additional thermo-modification and coating using graphite ink (by screen printing) were affected on strength and critical strain both the substrate and printed sensors. However, sensors critical strain at the open electrical circuit was not depended on thermo-modification of thermally-bonded nonwovens (NWM-1), it is slightly reduced after adhesive addition into ink composition. In contrary, critical strain and strength of the NWM-2 (needle-punch type nonwoven) was significantly increased after thermo-modification. Also, conductivity of sensors printed on NWM-2 was continued till the elongations close to substrate failure moment. As well maximum deformation value of NWM-2 – printed sensors was increased in a greater degree than for NWM-1 – printed sensors after PU-adhesive addition, it reached 80%.

Strain gauge sensors parameters can be defined by graphs presented in figure 6-10. Electrical resistance – deformation dependencies for sensors printed on initial nonwovens are shown in figures 6,7,8, they are described by power fit type \( f = k \epsilon^3 + n \epsilon^2 + b \) with high curve fitting probability (\( R^2 = 0.95 \)). AC-resistance increase ratio as a function of tenso-resistive sensors deformation (\( R/R_0 \)) after NWM-2 modification can be approximately described by linear functions (fig.10).

The exterior form of sensors printed on NWM-1 and NWM-2 substrates is presented in figure 11, the surface microstructure after NWM-1 bodying – in figure 12. Volt-ampere characteristics of all produced sensors have a linear character. This proves that the developed sensors produced by printing as well as mixed methods can be commercial utility as stable elements of different electron schemes.
Table 1. Technology and deformation of printed sensors

| Sample | Tm (°C) | PU-additive | Inka | Tension load, (N/sm) | Elongation (%) |
|--------|---------|-------------|------|---------------------|----------------|
|        |         |             |      |                     | At the substrate disruption | At the electrical open |
| NWM1   |         |             |      |                     |                |
| 1      | -b      | -           | -    | 5.7±1.1             | 100±8          | -               |
| 2      | -       | -           | +    | 10.7±2.1            | 100±7          | 45±2            |
| 3      | -       | +           | +    | 9.7±1.7             | 100±8          | 70±3            |
| 4      | 120     | -           | +    | 25.4±2.2            | 220±11         | 60±5            |
| 5      | 120     | +           | +    | 21.5±2.5            | 270±15         | 50±5            |
| NWM2   |         |             |      |                     |                |
| 6      | -       | -           | -    | 9±1.5               | 22±7           | -               |
| 7      | -       | -           | +    | 11.7±2.0            | 50±3           | 40±4            |
| 8      | 120     | -           | +    | 20.7±2.2            | 55±5           | 45±5            |
| 9      | 120     | +           | +    | 23±2.8              | 60±5           | 55±5            |
| 10     | 120     | +           | +    | 35.0±3.2            | 100±12         | 80±7            |

afor graphite ink
bInitial

DC-resistance of “NWM-1- CNT-inks” sensors (10 mm thickness) at the strainless mode is 1Ω order of magnitude, but printing quality is low, CNT-filled composition printing process was hindered due to plate clogging up as a CNT agglomeration result. In case of 0.001% surfactants addition both the printing quality and productivity were improved (figure 11b), the longitudinal deformation values were reached 150%, but at the same moment DC resistance was increased in 10 and more times. At AC resistance mode measuring (100kHz) surfactants addition affect was not so notable.

The gauge strain factor of sensors printed on NWM-1 by graphite ink at 100kHz frequency is 350 (relative units) at 20% sensor elongation; at 20-40% range elongation gauge strain factor is 800. Deformation measurement limits of NWM-2 printed sensors can be doubled by thermo-modification at 120°C (from 40 to 80%), also elongation values at the open circuit moment were increased in 3 times. The substrates bodied by the developed device [15] and printed by PU added inks are characterized by linear resistance dependence of deformation from 0 to 80%; the gauge strain factor was 450.

The electrical properties estimation during sensors storage at the damp atmosphere was aimed to quantification of action water vapour on sensor resistivity (sensors moisture fastness) as well as probability definition for humidity sensor creation if vapour impact will be significant. The absence of humidity influence on the ‘NWM-1 – graphite ink’ sensor workability was fixed after 2 weeks testing. In contrary, ‘NWM-1 – CNT ink’ sensors were indicated gradual resistance rise to the doubled value. The same types of the dependencies were characterized for both ‘NWM-2 – graphite ink’ and ‘NWM-2 – CNT ink’ sensors.
Figure 6. DC-resistance as a function of tenso-resistive sensors deformation, NWM-1 substrate.
1 – sample N2; 2 – sample N5 (see table 1).
1’ - R = 0.017ε + 0.048 graph
2’ - R = 0.026ε + 0.050 graph

Figure 7. AC-resistance as a function of tenso-resistive sensors deformation (at 100 kHz), NWM-1 substrate.
1 – sample N3; 2 – sample N5.

Figure 8. AC-resistance as a function of tenso-resistive sensors deformation (at 100 kHz), NWM-1 substrate
1 – sample N2; 2 – sample N4.

Figure 9. AC-resistance as a function of tenso-resistive sensors deformation (at 100 kHz), NWM-2 substrate.
1 – sample N9; 2 – sample N10.
4. Conclusion
So, as the result of the study the new tenso-resistive (strain-gauge) sensor for large elongations, printed on nonwoven substrates with varied strain ranges with using both commercially available conductive graphite inks and developed compositions CNT-filled in a presence of surfactants, PU adhesive and organic solvents additives. The sensor can be used for wearable electronics items, flexible systems and mechanisms, and also robotic-arms. The sensor advantage is ability strain ranges changing as well as deformation measuring limits accompanied by and economic and time rate (for shape variation) opportunities of mass-production printing.

References
[1] Nag A, Menzies B, Mukhopadhyay S C 2018 Sensors and Actuators A 276 226–236
[2] Cao J, Qin L, Liu J, Ren Q, Foo C, Wang H, Lee HP, Zhu J 2018 Ext. Mechanics Lett. 21 9-16
[3] White E L, Case J C, Kramer R K 2017 Sensors and Actuators A 253 188-197
[4] Nehir S O, Keskin A, Khea D , Onal C D 2015 Sensors and Actuators A 236 349-356
[5] An L, Lu T, Xu J, Wang Z, Xu M, Wang T J 2018 Int. J. of Mechanical Sciences 141 386-392
[6] Kumar A 2017 Manufacturing Letters 15 122-125
[7] Huang D, Liao F 2003 Journal of the Electrochemical Society 150 (7) 412-417
[8] Stoppa M, Chioriero A 2014 Sensors 14 (7) 11957-11992
[9] Kellie G 2016 Advances in Technical Nonwovens (Amsterdam: Elsevier) chapter 4 pp115-132
[10] Omrani F et al. 2016 Composites Part B 116 471-48
[11] Dal Pra I et al 2005 Biomaterials 26 1987–1999
[12] Liu Z H, Pan C T, Yen C K et al 2015 Applied Surface Science 346 291-301
[13] Pai C L et al. 2011 Polymer 52 6126-6133
[14] Savel’ev M A, Komarova L Y, Kondratov A P 2016 Izv.Vys.Uchebn. Zaved. Problem poligrafii i izdeiat dela 2 44-54
[15] Kondratov A P, Nazarov V G, Dedov A V, Ermakova I N, Komarova L Y Patent RF 162366
[16] Zuravleva G N, Komarova L Y, Kondratov A P 2015 *Izv. Vys. Uchebn. Zaved. Problem Poligrafii i izdat. dela* 1 20-26
[17] Bokova E C Faber-porous composites with bicomponent fiber using (Moscow: MGUDT) p 203
[18] Savel’ev M A, Kondratov A P 2015 *Izv. Vys. Uchebn. Zaved. Problem Poligrafii i izdat. Dela* 2 37-43
[19] Dedov A V, Ermakova I N, Zuravleva G N, Kondratov A P 2015 *Izv. Vys. Uchebn. Zaved. Problem Poligrafii i izdat. dela* 6 21-26
[20] Kondratov A P, Savel’ev M A, Zuravleva G N 2016 *Izv. Vys. Uchebn. Zaved. Problem Poligrafii i izdat. dela* 4 46-55
[21] Shakoor A, Baig GA, Tausif M, Gillani QZ 2016 *Dyes and Pigments* 136 865-872
[22] Li Z, Ye L, Shen J, Xie K, Li Y 2018 *Composites Communications* 7 23–29
[23] Khirotdin K, Cheng T S, Mokhtar K A 2016 *J. of Eng. and App. Sciences* 11 (10) 6619-6624