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Textronic Textile Product

Abstract
This article presents a concept and describes the procedure for manufacturing textronic textile products in the shape of a laminar structure with incorporated electro-conductive channels. We demonstrate that it is possible to introduce electro-conductive elements, such as copper wires, steel and metal plated synthetic fibres into the structure of stitched nonwovens. We also present an analysis of the electro-conductive and usage properties of the products manufactured, such as for example the bending rigidity.

Key words: *textronics, smart textiles, nonwovens, webs, electro-conductive channels, electrical wires, steel fibres, electro-conductive synthetic fibres, electrical resistance, bending rigidity.*

Introduction

The modern state of technique in general, and of electronics in particular, creates possibilities for integrating minimised sensors, electronic circuits and supply systems with textile products. The integration of electronic devices with textiles means that new products with improved features for the user can be offered. Textronics, as a developing science branch, aims to reinforce the basis of the technological field connecting the textiles with electronics and informatics [1]. The idea of textronics is based on one- and two-dimensional elements incorporated in the flat textile structure (Figure 1).

The military, the fire service, and other high-risk groups are important areas where the discussed technologies may be applied. The technology of interactive textiles facilitates human access to information; for example firemen, while putting out a burning house fire, work directly in the face of fire. Current protective clothing only protects against fire, but does not permit the transmission of any information between the fireman and the control centre, which would now be a possibility. Another interesting example of textronic application is also a fireman's uniform which enables the location of a man in action within the burning building to be specified [3].

Textronics mean that we can create products which enable effective supervision and protection of human health [1]. The inbuilt electronic systems support the products' interactivity by introducing sensors and electronic & piezoelectronic elements into the textile layers of the product. Most vital is the application of textronic products in rehabilitation and medical diagnostics. An example of a system for tele-rehabilitation is presented in Figure 2. The use of double-acting, touch-sensitive, interactive clothing elements and interfaces enables the medical specialist to supervise a patient's action.

Thanks to textronics, we can design shirts replacing electrocardiography apparatus; for example, the new 'Life Shirt' technology connects a T-shirt to a set of sensors monitoring 30 physiological signals [5]. Receivers and mobile phones composed into jackets may also be included into the concept of textronics. For example, a Swedish designer has developed gloves with a loudspeaker mounted in the index finger, and a microphone at the wrist. These gloves are connected by radio to a telephone, and are activated by hand gestures.

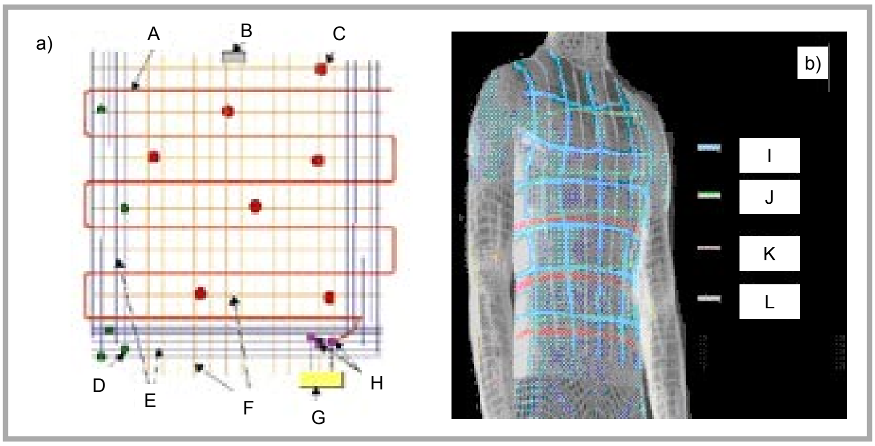

Figure 1. The idea of textronics [2]; a – scheme of a textile product with integrated elements of monitoring and control systems; b – multifunctional underwear; A – optical fibres, B – microphone, C – sensor, D – interface point, E – data buses, F – basic net, G – connectors, H – multifunctional processor, I – electro-conductive elements, K – optical measuring elements, L – rigidity improving elements, M – conductors carrying away electrical charges; ***Remark:*** *This figure is presented in colour on the internet edition of the journal (www.fibtex.lodz.pl).*

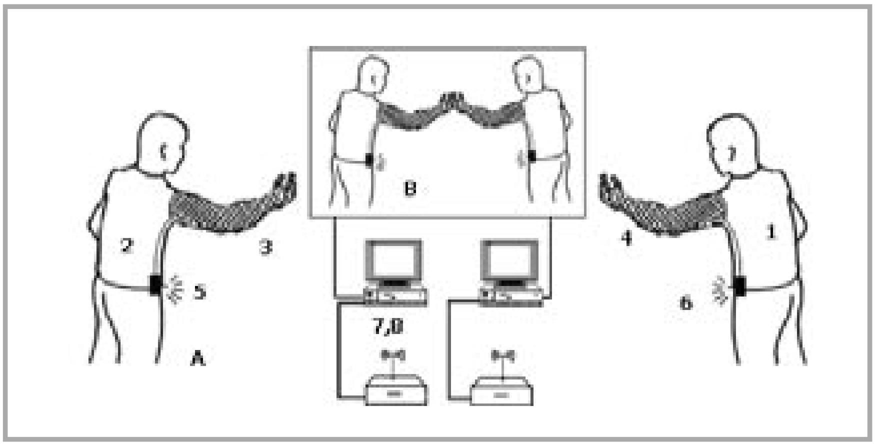

***Figure 2**. System of tele-rehabilitation [4]; A – real action, B – virtual action; 1 – medical specialist, 2 – patient, 3 – interactive clothing acting as the source of signals, 4 – interactive clothing acting as the recipient, 5 – radio-sender, 6 – radio receiver, 7 and 8 – computer monitoring of the actions of the medical specialist and the patient respectively.*

Including a network of electrical connections into the structure of the textile material is the essential first step in developing textronics. Clothing containing incorporated electrical connections which cannot be distinguished from the clothing used at present would be the ideal result. It will be possible to realise such a vision when user-friendly electronic woven & knitted fabrics and nonwovens are developed, in which the functional elements would be integral components of the product. Therefore the aim of the investigations presented was to approach the development of new textile technologies which would enable the inclusion of electronic circuits, electro-conductive-, piezo- and opto-electronic elements and other sensors into the textile structures.

Characteristic of test materials

Fibre characteristic

We used electro-non-conductive polypropylene (PP) staple fibres with linear density of 2.8 dtex and 60 mm staple length for manufacturing stitched nonwovens for use as the basic layers of a textronic product with electro-conductive channels.

Metallic, mainly copper wires are the simplest electro-conductors. However, the very good electrical conductivity of some polymer fibres may be a reason for applying them in particular cases as connectors instead of metallic wires [6]. For our investigations we used copper wires, and steel & synthetic fibres in the shape of staple fibres formed into bands.

We used the following kinds of electrical conductors:

- Generally available commercial bare and insulated copper wires with different diameters.
- Steel fibres in the shape of Bekinox steel staple fibres, manufactured by Bekaert Gmbh, Belgium, with linear density of 1.1 dtex and 40-50 mm staple length. These fibres are obtained by drawing wires made of chromium-nickel steel to the diameter of between ten and twenty micrometers. It should be emphasised that the addition of over 10% of such fibres to synthetic fibres additionally allows us to obtain products characterised by attenuation of electromagnetic radiation [7].
- Nonwovens manufactured from synthetic Nitril-Static (NS) staple fibres, made by the Textile Research Institute, Łódź (Poland), with a linear density of 3.3 dtex and 40 mm staple length. The electro-conductive properties of the NS fibres are obtained by coordinate-bonding of cupric sulphides with the nitric functional groups of these fibres [8], which yields an effect of electro-conductivity maintained over multiple washings.

The fibres' electrical resistance was measured in accordance with Polish standard PN-91/P-04871, whereas the resistance of the wires and metallic fibres were measured by generally used standard methods. The measuring cell described by the standard was in the shape of a cube, with electrodes of 0.06 ± .0005 m width and 0.05 m height, at a distance of 0.02 ± 0.0005 m. The mass of the PP and NS fibres was accepted as 11.0 g.

The resistivity of copper fibres is about 1.72×10^{-6} Ωcm, that the resistance of the NS fibre samples 143 Ω, and those of the PP fibre samples 7.6×10^{6} Ω. The resistance of the steel fibres was too small to measure with the use of the standard measuring cell, and a commonly-used M4650 digital multimeter was used for measurements. In order to use this meter, bands of the steel fibres were prepared with a length of 150 mm and linear densities of 2.5, 5, and 10 tex. The electrical resistance of bands was measured for fibres arranged longitudinally along the band, as well as for fibres twisted by 110 twists per meter. Although twisting the bands caused an increase in their resistance, all the steel bands' resistances fell within the range from 1 to some tens of ohms, comparable or significantly lower than those of the NS fibres.

Characteristics of the stitched nonwovens

Webs with transversal fibre arrangement were mechanically prepared for manufacturing the stitched nonwovens. The PP fibres were selected for nonwoven manufacturing thanks to their very low electro-conductive properties. A technological machine set from Asselin (France) was used, which included a carding machine, a vertical loop layer, and a preliminary stitching machine.

Before the principal stitching, the webs were stitched in advance, with a stitching number of Lp = 20 cm^{-2}. The depth of the preliminary stitching was 12 mm, the velocity of the cumulative lattice v = 0.55 m/min, and the feeding velocity machine-setting was 5.5. The technological process assumed that the nonwovens were manufactured with one side stitched. The nonwovens were obtained at different variants of needle selection, which was based on knocking out the needles from the stitching bar appropriately, in order to assure the safe passage of the incorporated textronic elements through the needle action field. The following three stitching numbers were used: 8, 11, and 15 cm^{-2}.

The depth of the principal stitching was 12 mm, the velocity of the cumulative lattice v = 0.2 m/min, and the feeding velocity machine setting was 2. 15×18×40×3.5 RB needles were used for manufacturing the nonwovens.

The webs were processed into double-layer structures. Five nonwoven variants were manufactured, characterised by a layer structure, with the particular layers consisting of PP fibre webs between which the electro-conductive elements (channels) were incorporated.

Characteristic of the electro-conductive elements incorporated into the nonwovens

The following types of electro-conductors were used for forming the conductive channels:

- ***Copper wires***. Insulated wires with polyvinyl insulation and diameters of 0.20 and 1.2 mm, and bare wires with diameters of 0.15, 0.22, 0.30, and 0.35 mm.
- ***Steel cords*** prepared from bands of steel fibres twisted to 100 twists per metre with the use of a twist-meter. The following linear densities (Tt) were obtained from the metallic textile cords: 2.5, 5, and 10 tex.
- ***Nitril-Static cords*** prepared from bands of NS fibres. Firstly, nonwovens were manufactured with the Asselin machine set. After carding, the fibres were stitched at a stitching number L_p = 20 cm^{-2}. The nonwovens obtained with an area mass of m_p = 71 g/m^2 were cut into 2 cm-wide bands according to the longitudinal and transversal fibre arrangement. Next, the bands obtained were twisted to 100 twists per metre with the use of a twist-meter. Further, the twisted and non-twisted nonwoven bands were incorporated as electro-conductive channels into the textronic product.

Incorporating the electro-conductive elements

In order to select the optimum solution, we used some different methods for creating the electro-conductive channels.

Based on the result of the preliminary investigations, we stated that the best processing method would be first introducing the electro-conductive elements into the layers by mechanical fastening, and then modelling the nonwovens mass using two variants of the mass of PP fibres. In order to decrease the risk of damaging the electro-conductive elements, some of the needles were rejected from the needle bar. The channels for the variants W1, W2, W3, and W4 were formed by this process.

In one of the variants, a sensor imitation was incorporated into the web layers together with its connecting wires. In this case, the stitching process needed the knocking-out of a given number of needles from the needle bar, in order to ensure that the sensor would not be exposed to the danger of the needle in action, and damaged. Before the needle selection, the needling density of the needle bar was 1/6 cm^{-1}. The needles were broken out in the middle part of the needle bar at a width of 18 mm, creating an 18-mm band without needles. The web prepared was stitched twice, in longitudinal and transversal directions, in order to better connect both the web layers.

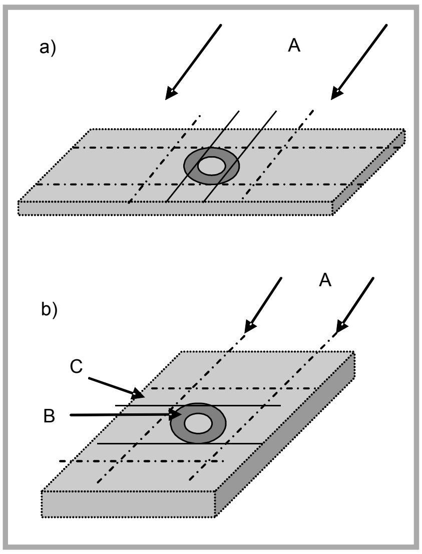

***Figure 3.** Scheme for manufacturing a textronic product with a sensor imitation incorporated; a – First stitching stage (the nonwoven stitched in the transversal direction of the fibre arrangement in the web); b – Second stitching stage (the nonwoven stitched in the longitudinal direction of the fibre arrangement in the web); the dotted lines identify the fields of needle selection in the needle bar; A – stitching direction, B – sensor imitation in the shape of a ring; C – the sensor's connecting wires.*

***Table 1.** Denotations of the web configurations and the electro-conductive elements used.*

Group of nonwoven variants	Nonwoven variant	Type of web arrangement	Electro-conductive elements incorporated into the nonwoven structure	Lp 1/cm^2
W 1	W 1.1.	nonwoven composed from 2 PP webs with area mass of 45 g/m^2	Cu(I) 0.20	11
	W 1.2.		Cu(B) 0.35	
	W 1.3.		Cu(I) 1.20	
	W 1.4.		Cu(B) 0.30	
	W 1.5.		Cu(B) 0.22	
	W 1.6.		Cu(B) 0.15	
	W 1.7.		SF	
W2	W 2.1.	nonwoven composed from 2 PP webs with area mass of 45 g/m^2	NS(W)	11
	W 2.2.		NS(SW)	
	W 2.3.		NS(P)	
	W 2.4.		NS(SP)	
W3	W 3.1.	nonwoven composed from 2 PP webs with area mass of 60g/m^2.	Cu(B) 0.35	11
	W 3.2.		Cu(I) 1.20	
	W 3.3.		Cu(B) 0.30	
	W 3.4.		Cu(B) 0.22	
	W 3.5.		Cu(B) 0.15	
	W 3.6.		SF	
W4	W 4.1.	nonwoven composed from 2 PP webs with area mass of 45 g/m^2 (*)	7×Cu(B) 0.22	15
	W 4.2.		5×SF	
W5		nonwoven composed from 2 PP webs with area mass of 45 g/m^2 (**)	5×SF	8

*NS – nonwoven of Nitril-Static fibres, SF – steel fibres, (L) – longitudinal direction, (T) – transversal direction, (S) – twisted, Cu(B) – copper wire bar, Cu(I) – copper wire insulated, L_p – stitching number (per cm^2), *) – the electro-conductive channels are placed at a small distance apart, in order to demonstrate the possibility of textronic material formation without the channels joining unwantedly, **) – a sensor imitation with connecting wires incorporated into the web layers; the wire diameters are given in mm after the wire denotation.*

The stitching scheme presented in Figure 3 shows the stitching stages; the dotted lines identify the fields of needle selection in the needle bar.

In order to obtain the final textronic product, bands were cut from the manufactured nonwovens which included the electro-conductive channels.

Each group of variants, which was characterised by the same technology for manufacturing the electro-conductive layers, was marked by the letter 'W' and a number. Each group included further variants distinguished by their type of electro-conductive element, marked by the second number. All variants and their denotations are presented in Table 1.

Determining the fibres' and nonwovens' properties

The morphological & electrical properties of the fibres, and the morphological & physical properties of the nonwovens were determined, as was the quality of the electrical elements included into the nonwoven structure checked.

The linear density (*Tt*) of the PP fibres, the fibre length (*l*), and electrical resistance (*R*) were determined in accordance with standards PN-ISO 1973:1999, PN-92/P-04761.02, and PN-91/P-487 respectively.

The nonwovens' area mass, its thickness (*d*), the nonwovens' air permeability (*Pp*) and the through resistance (*R*) were determined in accordance with standards PN-EN 29073-1:1994, PN-81/P-04612, PN-89/P-04618, and PN-91/P-04871 respectively.

All tests were performed at the temperature of 21 ± 1 °C and air relative humidity of 32 ± 2%.

Determining the properties of the textronic product

The textronic material was tested from the point of view of its electrical and usage properties. We decided that the continuity of the incorporated electrical

Table 2. Electrical resistance of the electro-conductive elements incorporated.

Lp	Kind of element	R, Ω Before stitching
1	Cu(I) 1.2	2.5
2	Cu(I) 0.2	2.6
3	Cu(B) 0.35	2.59
4	Cu(B) 0.30	2.57
5	Cu(B) 0.22	2.71
6	Cu(B) 0.15	3.37
7	NS(T)	130
8	NS(L)	400
9	NS(TS)	160
10	NS(LS)	88
11	SF 10tex	116.0
12	SF 5tex	81.2
13	SF 2.5tex	57.23

elements and the textronic material's usage properties, such as bending rigidity, would be the quality criteria of the product.

Table 2 presents the average measurements of the electrical resistance of the electro-conductive elements incorporated into the nonwoven layers before stitching. We stated that the stitching process did not cause any damage to the electrical elements, as the electrical resistance of the copper wires did not change, and those of the textile electro-conductive elements changed only by a few percentage points. This latter was caused by the stitching process, which slightly changed the fibres' arrangement.

In addition, thermovision tests were carried out in order to check the elements' continuity. A PM290 Inframetrix camera from Thermacam (USA) was used; the camera was calibrated before the tests. A temperature scale is shown on each thermogram in conventional units. The upper temperature value is 34.9 °C, whereas the bottom value is 16.2 °C. A given colour (visible only on the internet edition of the journal's issue) is related to each temperature sub-range.

The textronic nonwovens with their incorporated electrical elements were placed on a plate and an electrical voltage source was connected to the ends of the elements. The electrical potential difference at the ends of the incorporated elements was selected according to each kind of element, as considering the great differences in the electrical resistances between the copper wires and the textile elements, a considerably smaller amount of energy (heat) would be released in the latter, and the visualisation of the thermal effects would be insufficient. The elements were grouped on the plates according to the type of electro-conductive channel, as shown in Figure 4. The upper photo presents copper wires, the middle the steel elements, and the bottom photo presents the synthetic NS elements. All designations are given according to Table 2.

An analysis of the thermovision images from the final products evidently proves that the continuity of the conductive elements was not broken.

The variety of the heating intensity of the elements incorporated into nonwovens, and at the same time the differences in the temperature distribution visible on the thermograms, result from the differences in the electrical resistance of the incorporated elements, and by the copper wires additionally from the fact that bare and insulated wires were tested. The worst images were obtained for the thick wires, such as those with a diameter of 1.2 mm, whereas the best images came from elements incorporated together at small distances. It should be emphasised that the latter did not show any destruction either.

An analysis of the images obtained allows us to state without doubt that the stitching did not break the elements' continuity, and did not change the resistance of the elements. Considering the quality of the channels' electro-conductivity, we could state that each kind of the variants we tested can be used while manufacturing the textronic product.

Morphological and physical properties of the stitched nonwovens

Considering that the variants of one group (for example from W1.1 to W1.7) were manufactured from one kind of nonwovens, the tests of morphological parameters and air permeability, as well as the results analysis, were carried out for only one variant of the group (for example W1.1 was tested for the whole W1 group). The same was done for W2, W3, W4, and W5.

The morphological tests, the tests of electrical properties, and the determination of air permeability were carried out with nonwoven layers before manufacturing the final textronic product. This choice was motivated by the conditions of the test methods. Bending rigidity was one of the estimation criteria for the quality of the product with incorporated electro-conductive channels, and so this property was tested before and after the electro-conductive channels were incorporated into the nonwoven structure.

Through resistance of nonwovens

The test results listed in Table 3 present the values of through resistance. The resistance values are values of 15 measurements carried out at a temperature of 21 ± 1 °C and relative humidity of 32 ± 2%.

Table 4 presents the test results of the through resistance of nonwovens with incorporated electro-conductive channels of the variants from W1.1 to W1.7.

The through resistance of the nonwovens with the electro-conductive elements is higher than without the elements. This is caused by the local increase in the non-

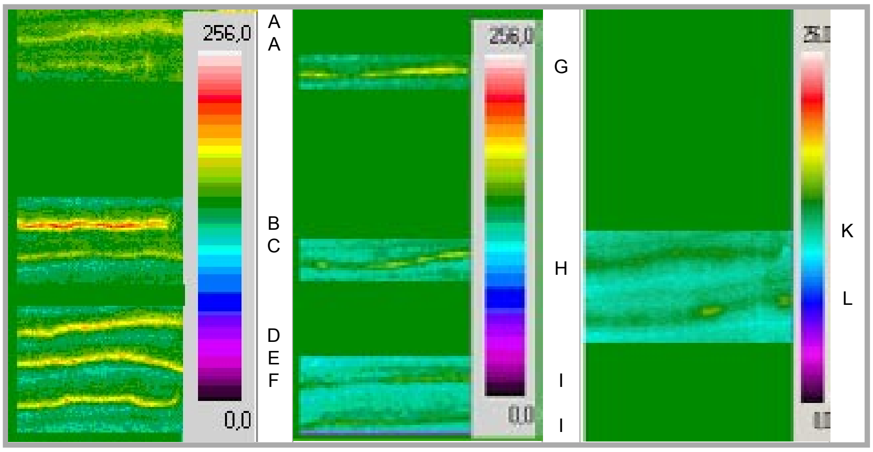

***Figure 4.** Thermograms of nonwovens with electro-conductive channels; A – Cu(I) 1.2, B - 7×Cu(B) 0.22, C –Cu(I) 0.20, D – Cu(I) 0.35, E – Cu(I) 0.22, F – Cu(I) o.15, G – SF band of 10 tex, H – SF band of 5 tex, I – SF band of 2.5 tex, K – NS, L – NS(S); **Remark:** This figure is presented in colour on the internet edition of the journal (www.fibtex.lodz.pl).*

Table 3. Through resistance (R) of nonwovens without incorporated electro-conductive channels.

Variant of nonwoven groups	R, Ω
W 1	2.01 ×10^{9}
W 2	1.88 ×10^{9}
W 3	2.27 ×10^{9}
W 4	5.07 ×10^{9}
W 5	3.20 ×10^{9}

Table 4. Test results of through resistance of nonwovens with incorporated electro-conductive channels of the variants from W1.1 to W1.7.

Variant designation	Variant description of the W1 group	R, Ω
W 1.1	PP with Cu(I) 0.20	2.75 ×10^{9}
W 1.2	PP with Cu(B) 0.35	2.90 ×10^{9}
W 1.3	PP with Cu(I) 1.20	3.00 ×10^{9}
W 1.4	PP with Cu(B) 0.30	3.30 ×10^{9}
W 1.5	PP with Cu(B) 0.22	3.50 ×10^{9}
W 1.6	PP with Cu(B) 0.15	2.75 ×10^{9}
W 1.7	PP with ST	2.80 ×10^{6}

Table 5. Through resistance (R) for nonwoven variants of the group W2, with incorporated NS electro-conductive elements.

Variant designation	Variant description of the W2 group	R, Ω
W 2.2 and W 2.4	PP NS(S)	0.065 ×10^{9}
W 2.1 and W 2.3	PP NS	0.210 ×10^{9}

woven's thickness at the places where the elements were inserted. On the other hand, incorporating these elements did not change the nonwovens' electro-insulation properties.

Table 5 presents the measurement results of through resistance for the variants W2.1 – W2.4 for nonwovens with incorporated NS electro-conductive elements, and Table 6 presents those results of the variants W3.1 – W3.5, W4.1 – W4.2, and W5.1 – W5.2 with incorporated copper and steel elements.

The results presented in Tables 4 to 6 allow us to analyse the dependency of the nonwovens' through resistance on the type of the incorporated electro-conductive channels. The nonwovens with channels of steel fibres were characterised by the smallest through resistance. The small percentage content of these fibres within the range of 0.5%, resulting from the incorporated steel fibre elements, caused a decrease in the nonwoven's through resistance from 10^{9} to 10^{7} Ω. The similar NS fibre content also caused a decrease in the nonwoven's through resistance, this time of about one order of magnitude. It should also be stressed that the resistance of the nonwovens of the variant W2 depended on the twist (twisted or not) of the steel fibre nonwoven bands. Applying a twist to the NS nonwoven bands caused a decrease in the final nonwoven through resistance, from the value of R = 2.1×10^{8} Ω to R = 0.65×10^{8} Ω. The resistance decrease was caused by drawing single steel fibres from the electro-conductive channels into the web structure while stitching the webs.

On the other hand, the incorporation of the electro-conductive elements into the nonwoven structure do not cause any visible decrease in the electro-conductivity of the nonwovens themselves.

Analysing the results of resistance measurements allows us to conclude that all the variants presented are suitable for manufacturing a textronic textile product. Although these variants containing electro-conductive elements obtained from textile structures were characterised by a decreased through resistance, in comparison to those with copper wires (R = 10^{9} Ω), their through resistance of 10^{7} Ω allows us to conclude that the nonwovens with incorporated electro-conductive textile structures are characterised by suitable electro-insulation features for the textronic products we have manufactured.

Area mass, thickness, apparent density, and air permeability

Table 7 presents the area mass (m_p), thickness (G) and air permeability (P_p)

Table 6. Through resistance (R) for nonwoven variants of the groups W3, W4 and W5 with incorporated NS electro-conductive elements.

Variant designation	Variant description of the W3. W4. W5 group	R×10^{-9}, Ω
W3.1	PP with Cu(B) 0.35	4.50 ×10^{9}
W3.2	PP with Cu(I) 1.20	3.20 ×10^{9}
W3.3	PP with Cu(B) 0.30	4.30 ×10^{9}
W3.4	PP with Cu(B) 0.22	3.80 ×10^{9}
W3.5	PP with Cu(B) 0.15	4.00 ×10^{9}
W3.6	PP with SP	5.00 ×10^{6}
W4.1	PP with Cu(B) 0.22	7.78 ×10^{9}
W4.2	PP with SP	17.5 ×10^{6}
W 5	PP with a sensor imitation, with connecting wires incorporated into the web.	4.10 ×10^{9}

of nonwovens manufactured with incorporated electro-conductive elements. In order to facilitate the analysis of the results, a description of each variant is included in the table.

The results obtained show that the nonwovens manufactured from webs of the same area mass (the variants W1, W2, W4, and W5) are characterised by an area mass within the range from 92 g/m^{2} to 106 g/m^{2} (the differences were caused by fluctuations of the webs during the stitching process), whereas the nonwovens of variant W3 are characterised by an area mass of 127 g/m^{2}.

The nonwovens' air permeability is strongly connected with the apparent density. An increase in the nonwovens' area mass resulted in an increase in the apparent density, and at the same time a decrease in the air permeability. One example is the nonwovens of the group W3 in relation to the remaining groups.

Table 7. Area mass (m_p), thickness (d), and air permeability (P_p) of the nonwovens manufactured with incorporated electro-conductive channels.

Group of variant	m_p g/m^{2}	d, mm	P_p, dm^{3}/m^{2}s	Variant description
W1	92	2.63	427.42	Nonwoven of two PP webs, each with area mass of 45 g/m^{2}; generally available copper wires with different diameters and elements of steel fibres are the electro-conductive elements.
W2	106	2.85	336.74	Nonwoven of two PP webs, each with area mass of 45 g/m^{2}; nonwoven of Nitril-Static fibres as electro-conductive elements.
W 3	127	3.15	239.22	Nonwoven of two PP webs, each with area mass of 60 g/m^{2}; generally available copper wires with different diameters and elements of steel fibres are the electro-conductive elements.
W4	100	2.84	416.01	Nonwoven of two PP webs, each with area mass of 45 g/m^{2}; generally available copper wires with a diameter of 0.22 mm and elements of steel fibres are the electro-conductive elements; the electro-conductive channels were placed side by side in order to prove the possibility of joining the channels, and use them as parallel connected conductors.
W5	106	2.69	419.63	Nonwoven of two PP webs, each with area mass of 45 g/m^{2}; sensor imitation with connecting wires was incorporated between the web layers; stitching was carried out in two stages.

Table 8. Bending rigidity measurement results; all variant are manufactured of PP with out electro-conductive elements (mark by '-', or with the particular electro-conductive elements; C - bending length, G - bending rigidity.

Variant denotation	Variant description nonwovens of the W1, W2, W3, and W4 group	C, cm	G, mNm
W 1	-	3.09	0.27
W 1.1	Cu(I) 0.20	3.35	0.35
W 1.2	Cu(B) 0.35	7.95	4.62
W 1.3	Cu(I) 1.20	12.15	18.0
W 1.4	Cu(B) 0.30	3.34	0.34
W 1.5	Cu(B) 0.22	3.43	0.37
W 1.6	Cu(B) 0.15	3.22	0.31
W 1.7	SF	4.90	1.08
W 2	-	3.13	0.65
W 2.2 and W 2.4	NS(S)	4.50	1.41
W 2.1 and W 2.3	NS	4.50	1.41
W 3	-	4.24	0.97
W 3.1	Cu(B) 0.35	5.00	1.59
W 3.2	Cu(I) 1.20	13.60	31.90
W 3.3	Cu(B) 0.30	6.00	2.74
W 3.4	Cu(B) 0.22	5.65	2.29
W 3.5	Cu(B) 0.15	5.55	2.17
W 3.6	SF	4.25	0.97
W 4	-	3.52	0.44
W 4.1	Cu(B) 0.22	3.45	0.41
W 4.2	SF	3.45	0.41

According to our experience, the stitching process itself was the reason for these differences.

In the next stage, we tested the bending rigidity of the textronic product manufactured. In order to prepare the samples for the rigidity testing, firstly the textronic product was formed from the nonwovens manufactured, with dimensions in accordance with the standard, and with a longitudinal arrangement of the electro-conductive elements. The test was performed in accordance with standard PN-73P-04631. The bending rigidity was determined by the constant angle method, and carried out for all variants for the nonwovens, without electro-conductive elements and with the elements incorporated.

Table 8 presents the results of the bending rigidity measurements (bending length and bending rigidity) for the variant groups W1, W2, W3, and W4 without the incorporated electro-conductive elements, and for the particular variants with the different elements incorporated. In order to facilitate the analysis, the variants are described by the appropriate designations. The bending rigidity tests were not carried out for nonwovens with incorporated sensor imitations, as these textronic products were only prepared with the aim of proving that the technology we applied is also suitable for incorporating elements of relatively large dimensions.

The nonwovens manufactured differ mutually in the value of bending rigidity within the range from 0.27 to 0.97 mNm. The differences were caused by the variety of the nonwovens' structure; firstly by the area mass and the thickness, as these morphological nonwovens' parameters are decisive for their rigidity. Among the group W1, the variants W1.2 and W1.3 were characterised by the greatest bending rigidity caused by the greatest diameters of the incorporated copper wires (0.3 mm and 1.20 mm), and in the case W1.3 additionally of the wire's insulation. A similar situation was noted among the W3 variants, where the variants W3.1 and W3.2 were characterised by the greatest rigidity for the same reason.

As none of the materials used as electro-conductive channels were not damaged during manufacturing, the most appropriate technology for the final product was chosen on the basis of the values of electrical resistance and bending rigidity.

The investigation presented herein indicates that the bending rigidity of the textronic products manufactured is strongly connected with the presence of the elements incorporated. The rigidity is higher for all structures with incorporated elements.

Almost all the nonwoven variants with incorporated electro-conductive elements are characterised by similar values of bending rigidity within the range of 0.4 mNm to 1.64 mNm. Only the nonwovens of variants W1.3 and W3.1 are characterised by bending rigidity values of 18.0 mNm and 31.9 mNm respectively, and this is why these variants should be rejected from those suitable for manufacturing.

Conclusions

On the basis of the research carried out, the following conclusions can be drawn:

- It was proved that electro-conductive channels and measuring sensors can be incorporated into the nonwovens manufactured by stitching.
- The textile electro-conductive elements used are suitable for incorporation into the final textronic product, as the incorporation diminished the through resistance of the product only insignificantly (in this case).
- The copper wires used are also suitable for obtaining electro-conductive channels, under the condition that they are not too thick.
- Wires of too great diameters and with an electrical insulation should be eliminated
- The parameters of the technological process should be selected so that the continuity of the elements incorporated would not be broken; we proved that this is possible.
- Considering the quality and usage properties of the final textronic product, steel fibres are the most suitable material for manufacturing the electro-conductive channels.
- We demonstrate that a textronic product can be manufactured by the stitching technique.
- A textronic product was manufactured which was designed for acquiring data and transmitting electrical signals while monitoring human physiological parameters.

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