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Electrical Parameters of Conductive Structures for Smart Textiles

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ABSTRACT

The increasing adoption of smart textiles for military applications and operations is saving lives and changing the ways that militaries worldwide operate. Military clothing plays an essential role in protecting soldiers from warfare and combat elements. Textile structures with tubular shapes were designed and made by knitting technologies using metallic yarns (Shieldex, Filix, AgSiS, etc.) with linear resistivity between 3–300 Ω/m, to integrate into the block diagram of a primary haemostasis device intended for combatants on the battlefields. The surface resistance of the fabrics with metallic yarns was measured and the conductivity was calculated. The best value of conductivity was obtained by the textile structure made from 100% metallic yarns (32.808,16 S/m). The descriptive statistical analysis was elaborated for variable resistivity (mOhm) for all textile conductive structures in both parallel and perpendicular directions on conductive yarns. The histograms and the boxplot graphs for the analysed variable are presented. Skewness and the vault indicators (kurtosis) are analysed.

Keywords: Conductivity, Textiles, Knitting, Resistivity, Descriptive

INTRODUCTION

As an intrinsic property of materials, electrical conductivity is the measure of the amount of electric current a material is capable of carrying or its ability to carry electric current or electric charges. It involves the movement of electrically charged particles through a transmission medium. Conductive materials exhibit high electron mobility or in other words many free electrons (Raji et al., 2017).

As technology becomes increasingly mobile, the next step is the integration of advanced devices and functionalities into flexible textile substrates, which, when combined with different solutions, e.g., the Internet of Things (IoT), big data analytics, and artificial intelligence (AI), offer a wide range of actions, in the field of virtual reality, inter-device communications and between cyber-physical systems with a strong impact on the fourth industrial revolution (Fernández-Caramés et al., 2018).

The generic term metal fiber, as adopted by the U.S. Code of Federal Regulations (CFR), is defined as "a fiber composed of metal, metal coated with plastic, plastic coated with metal, or a core coated entirely with metal."

Because of their conductivity, conductive metal yarns are typically used for carrying current between electrical sources and electronic devices, or for carrying information from these devices to the processing part of the material (Choudhry et al., 2021, Cherston et al., 2019). The best electrical conductor, under normal temperature and pressure conditions, is metallic silver. Other conductive materials are copper, gold, aluminium, iron, steel, brass, bronze, mercury, and graphite (Cherston et al., 2019). Ensuring electrical conductivity in textiles is surrounded by multiple exploitable effects, such as antistatic effect, antimicrobial, electromagnetic shielding, and thermal effect with a role in ensuring safety and comfort, and in some cases aesthetics. Electroconductive textiles (fibers, yarns, or flat, tubular, or 3D textile surfaces), both for wearable and non-wearable purposes, thanks to attributes such as mechanical flexibility, long-term durability, stability and resilience under harsh conditions, are an essential component of flexible and stretchable electronics, so a multitude of techniques have been developed to integrate/apply conductive compounds, which significantly influence the electrical properties of textiles as well as the wash/wear durability of the final product (Zhu et al., 2021)

DESIGN AND DEVELOPMENT OF CONDUCTIVE TEXTILE STRUCTURES

E-textiles have the great advantage of the flexibility of textiles. They can be tailored to the human body, allowing a person to effectively "wear" electronic devices. Ballistic protective equipment is designed and made to protect the upper part of the human body without including the upper/lower limbs which remain exposed to external stressors (shooting, cutting, etc.) that can lead to the death of the combatant due to blood loss. The solution addressed in this research consists of the detection of the wound employing a conductive textile structure containing metallic threads. When a metallic thread in the structure is punctured (bullet, knife, etc.), it will generate an electrical signal interpreted by the control unit to operate an air pumping system that activates a pneumatic tourniquet (Figure 1), which will stop the bleeding.

Figure 1: Jacket with the first layer having conductive yarns.

The experiments aimed to develop textiles with a sleeve-specific tubular geometry (arm, forearm, and elbow) to ensure continuity of the electrical circuit and avoid interlocking seams. The main characteristics of the metallic yarns are shown in Table 1.

Table 1. Characteristics of metallic yarns.

No.	Characteristics		Yarns variants				
				V2			
			V1 	V2.1 	V2.2 	V2.3 	V3 
1.	Composition,%		PA6.6/ Ag- 99,9%	PA- core/Ag mantle	PES- core/Ag mantle	PA- core/Ag mantle	78% metallic yarn /22% PES yarn
2.	Finesses	Tex (Nm)	15x2 (66,6/2)	36,1x1 (27,70/1)	126,1x1 (7,93/1)	19,9x1 (50,25/1)	18,94x2 (52,8/2)
		Tex (Dtex)	152x2 (136,8x2)	361x1 (324,9x1)	1261x1 (1134,9x1)	199x1 (179,1x1)	189,0x2 (207,9x2)
3.	CV,%		0,38	2,91	2,16	3,14	1,58

The yarn length density is in the range: of 12.6x2 (78.93/2) Tex (Nm)-126.1x1 (7.93/1) Tex (Nm) and the linear electrical resistance is best for V2.2-3Ω/m and highest for V1 (<300 Ω/m).

Tubular textile structures (Figure 2) made of 100% metallic yarns and metallic yarns in combination with 100% elastane yarns were made on circular knitting machines type SANGIACOMO - HT1 with fineness 14, with 168 needles, 7mm needle tongue, hofa thick. Go302 303. The structure of the main steps of the specialized program used for making tubular knitwear on circular knitting machines included 68 steps (sequences Figures 3 a, b, c.).

Figure 2: Tubular conductive textile structure.

Figure 3: Programme structure a) elastic shafts b) triangles c) lifting cylinder.

Table 2 shows the physical and mechanical characteristics of tubular knitted fabrics made on circular knitting machines.

Table 2. Characteristics of tubular conductive structures.

No.	Characteristics		U.M.	Variants of tubular knitted fabrics				
				T.V1	T.V 2.1	T.V 2.2	T.V 2.3	T.V3
1.	Metallic yarn length		cm/ 5cm	32 yarn AGIS100D/28 PA/ 7 yarn fire elastane yarn	32 yarn AGIS 200D/ 30 PA /8 yarn elastane yarn	17 yarn AGIS Lib 40 /15 PA/6 yarn elastane yarn	22 yarn Statex 117/17 PA/8 yarn elastane yarn	28 yarn 5340/24 PA/7 yarns elastane yarn
2.	Mass		g/m^2	409,6	394,4	621,2	362,4	356,8
3.	Density	Dv	No. of stitch course/10 cm	110	100	90	114	130
		Do	No. of stitch wale/10 cm	110	100	70	100	110
4.	Breaking strength	Dv	N	622,91	580,93	156,57	114	130
		Do		143,44	135,6	123,54	81,19	47,52
5.	Elongation at break	Dv	%	114,00	95,17	38,70	105,83	101,36
		Do		93,33	86,2	59,1	78,47	73,37
6.	Thickness		mm	1,92	1,79	1,89	1,85	1,82
7.	Resistance to bursting		kPa	160,3	166,3	147,9	72,3	102,3
8.	Deformation		mm	70,0	70,0	44,4	70,0	70,0

The level of elongation (deformation) of the different areas of the tubular structures (Figure 4) was determined with the CTME apparatus. The results for the T.V2.3 structure shown in Table 3 show no significant differences between the zones.

The length of the metallic thread in the knitted structure varies from 17 cm/5 cm in the T.V2.2 variant to 32 cm/5 cm in the T.V2.3 variant, which is determined by the difference in thickness in the horizontal direction: respectively 70 wales/10 cm (T.V2.2) and 110 wales/10 cm (T.V2.3) and in the vertical direction: 90 wales/10 cm (T.V2.2) and 110 wales10 cm (T.V2.3).

Table 3. Deformation of structural areas.

No.	Area	Dimensions (relaxed), ± cm	Elongation, ± cm
1	a1	8,5±0,5	28,0±2,0
2	b2	8,0±1,0	27,0±2,0
3	d3	8,0±1,0	27,0±2,0
4	e	graduation	25,0±3,0
5	f4	6,0 ±0,5	22,0±1,0

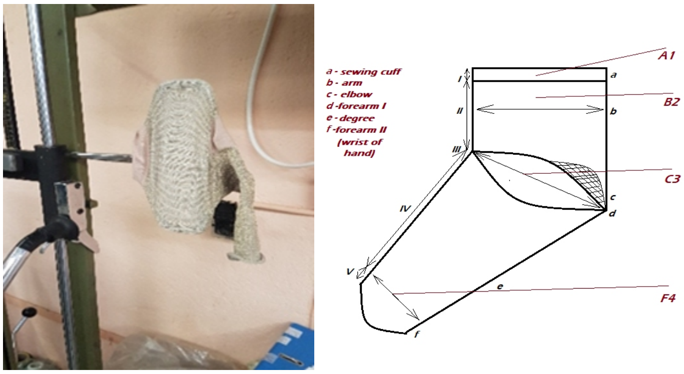


Figure 4: a) CETME; b) deformation zones.

The thickness of the tubular structures made on circular knitting machines is in a range with relatively close limits: 1.79 mm (T.V2.1) and 1.92 mm (T.V2.3).

The burst strength is highest for the T.V2.1 variant (166.3kPa) but with the lowest deformation value of 44.4 mm; the other variants show about twice as high deformation values (70 mm) at relatively close burst strength values (kPa).

The abrasion resistance test (40,000 cycles) showed no stitch breakage in all variants of tubular knitted structures made on the circular knitting machine.

CONDUCTIVITY OF TEXTILE STRUCTURES

The surface resistance (Rs) of textile structures containing metallic yarns was measured using the CROPICO 4000 Multimeter, consisting of two parallel linear electrodes placed 30 mm apart. The layout of the set-up is shown in Figure 5a and the image of the device in Figure 5b.

The size of the measurement sample: square with a side of 2.54 cm (area - 6.45 cm^2). Measurements were made in two directions of the sample: in the direction parallel to the position of the conducting threads in the textile structures and the direction perpendicular to them.

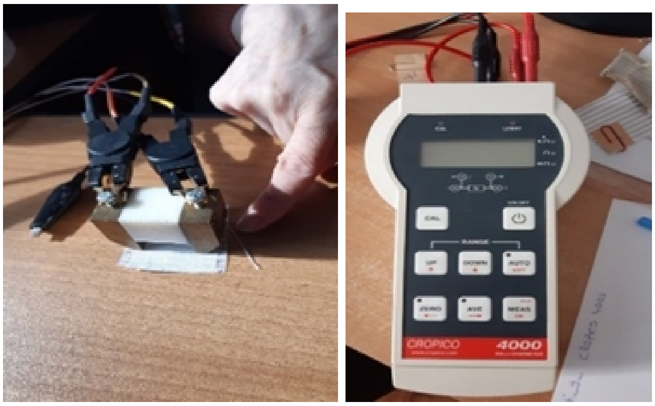


Figure 5: a) Layout of the setup; b) multimeter image.

The results were expressed in Ohm/m^2. To calculate the resistivity of the material, geometrical parameters of the textile structures were also introduced. The physical relationship for the electrical resistance Rs and the electrical resistivity of a given material ρS are given in relation (1) and (2) [1]:

$$R_S = \frac{U}{I_S} \tag{1}$$

$$\rho_S = \frac{\frac{U}{L}}{\frac{I_S}{D}} \tag{2}$$

With the following notations:
U – applied voltage;
I_S – the measured electric current;
L – the length of the specimen placed between the two electrodes;
D – fabric width.

The electrical resistivity relation (2) was derived for the case of parallel electrodes and the rectangular shape of the sample from the general electrical resistivity relation expressed by equation (3).

$$\rho = \frac{U}{I} \cdot \frac{D \cdot g}{L} = R \cdot \frac{D \cdot g}{L} \tag{3}$$

Where g - thickness of the material. Thus, the thickness g of textile structures was also included in the calculation of electrical conductivity, because it is considered a relevant parameter and to be able to express conductivity in [Siemens/m].

The general expression of electrical resistivity is thus expressed in [Ohm-metre]. The electrical resistance for 1 m^2 of textile material was calculated, with values expressed by the parameter R in [Ohm]. All geometrical parameters of the sample were measured (fig.6) [L= 0.03 m, D= 0.02 m, U-10V and g (see Table 2)], and the electrical resistivity was calculated according to relation (3) in [Ohm-metre]. The electrical conductivity of textile structures with metallic yarns is given by equation 4 since the conductivity is calculated with the inverse relation of the resistivity:

$$\sigma = \frac{1}{\rho} \tag{4}$$

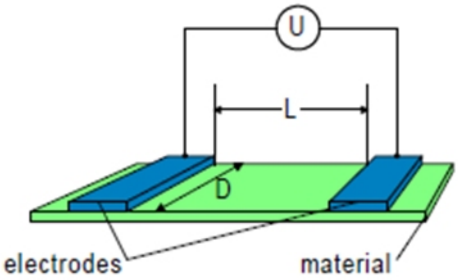


Figure 6: Sample measurement parameters.

Tables 4 and 5 show the resistivity and conductivity values obtained for the variants of conductive knitwear with tubular geometry made on SANGIACOMO - HT1 knitting machines.

Table 4. Paralleled direction conductivity.

Characteristics	Variants				
	(T.V2.3)	(T.V1)	(T.V3)	(T.V2.2)	(T.V2.1)
Val 1	60	175.6	-	30.34	207.5
Val 2	62.2	168	-	23.16	153.1
Val 3	88.8	180.7	-	22.94	69
Val 4	70	165	-	21.3	59.9
Average [mOhm/6.45cm^2]	70.25	172.33	-	24.44	122.38
[Ohm/6.45 cm^2]	0.0703	0.1723	-	0.0244	0.1224
Thickness [mm]	1.92	1.57	-	1.89	1.79
g [m]	0.00192	0.00157	-	0.00189	0.00179
Resistivity. [Ohm m]	0.000089	0.000179	-	0.000030	0.000145
Conductivity. [S/m]	11233.33	5600.26	-	32808.16	6916.88

The analysis of the conductivity values shows that in the direction parallel to the conductive yarns of the tubular textile structures made on circular machines, the best values were achieved by the T.V2.2 variant (32. 808 S/m) made of yarns with linear resistance of 3 Ω/m, followed by T.V2.3 (11,233.33 S/m), made of wires with linear resistance 135 Ω/m and T.V2.1 (6,916.88 S/M) made of wires with the linear electrical resistance of 70 Ω/m. In the direction perpendicular to the conductive yarns of the textile structures, the best electrical conductivity values were obtained for the textile structures T.V2.2 (9.071,20 S/m), T.V2.3 (7.987,26 S/m) and T.V2.1 (5.770,95 S/m). The thickness (mm) of the tubular textile structures with the best conductivity values on both systems did not differ significantly (1,89 mm - 1,92mm) (see Table 4). The largest difference is found in the length of the metallic yarns in the textile structures: 17 wales/5cm in T.V2.2 and 32 wales/5m in T.V2.3 and T.V2.1.

Table 5. Paralleled direction conductivity.

Characteristics	Variants				
	(T-V2.3)	(T-V1)	(T-V3)	(T-V2.2)	(T-V2.1)
Val 1	86.1	218	10050	29.9	183.4
Val 2	102.5	217	8860	106.8	131.1
Val 3	84.6	226.2	13910	118.4	135.4
Val 4	122	-	-	98.4	136.8
Average [mOhm/6.45cm^2]	98.80	220.40	10940.00	88.38	146.68
[Ohm/6.45 cm^2]	0.0988	0.2204	10.9400	0.0884	0.1467
Thickness [mm]	1.92	1.57	1.82	1.89	1.79
g [m]	0.00192	0.00157	0.00182	0.00189	0.00179
Resistivity [Ohm m]	0.00013	0.00023	0.01314	0.00011	0.00017
Conductivity [S/m]	7987.26	4378.70	76.10	9071.20	5770.95

The descriptive statistical analysis was elaborated for variable resistivity (mOhm) for all 5 textile conductive structures in both directions. The histograms and the boxplot graphs for the analysed variable are presented in Fig. 7 a) parallel direction and b) perpendicular direction.

Parallel Direction

Skewness indicators have positive values for the resistivity of all textile tubular structures, the normal distribution curve moves away from the middle, moving to the right. The vault indicators (kurtosis) have negative values for T.V1: −2,941 and T.V2.1: −3,187 the curves being platykurtic and positive T.V2.3: 2,619 and T.V2.2: 3,296 curves being of leptokurtic type.

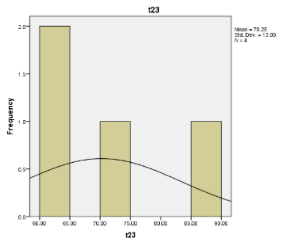
Perpendicular Direction

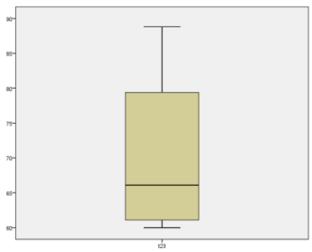
Skewness indicators have positive values for the resistivity of the variants: T.V2.3:0.955, and T.V2.3:1,941 the normal distribution curve moves away from the middle, moving to the right, and negative values for the variants: T.V1: −1.992, T.V3: −1,181 and T.V2.2: −1,747 the normal distribution curve moves away from the middle, moving to the left. The vault indicators (kurtosis) have negative values for T.V2.3: −0,719 the curves being platykurtic and positive T.V1: 3,973, T.V3: 2,131 and T.V2.3:3,817 curves being of leptokurtic type.

Statistics

		t23	t1	t2.2	t2.1
N	Valid	4	4	4	4
	Missing	0	0	0	0
Mean		70.2500	172.3250	24.4350	122.3750
Median		66.1000	171.8000	23.0500	111.0500
Mode		60.00ª	165.00ª	21.30ª	59.90ª
Std. Deviation		13.08982	7.14674	4.02318	70.57456
Skewness		1.422	.271	1.737	.474
Std. Error of Skewness		1.014	1.014	1.014	1.014
Kurtosis		1.674	-2.941	3.296	-3.187
Std. Error of Kurtosis		2.619	2.619	2.619	2.619
Sum		281.00	689.30	97.74	489.50

a. Multiple modes exist. The smallest value is shown





		t2.3	t1	t3	t2.2
N	Valid	4	4	4	4
	Missing	0	0	0	0
Mean		98.8000	165.3000	8205.0000	88.3750
Median		94.3000	217.5000	9455.0000	102.6000
Mode		84.60ª	.00ª	.00ª	29.90ª
Std. Deviation		17.46291	110.27705	5879.40190	39.83636
Variance		304.953	12161.027	34567366.667	1586.936
Skewness		.955	-1.992	-1.181	-1.747
Std. Error of Skewness		1.014	1.014	1.014	1.014
Kurtosis		-.719	3.973	2.131	3.217
Std. Error of Kurtosis		2.619	2.619	2.619	2.619
Sum		395.20	661.20	32820.00	353.50

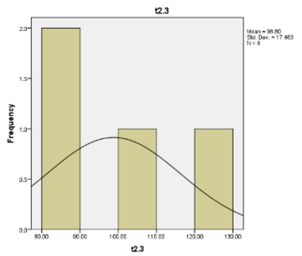


Figure 7: Histogram and box plot-a) parallel direction b) perpendicular.

CONCLUSION

Shieldex, AgSIS and Filix type conductive yarns with fineness between: 126.1x1 dtex –748.0x1 dtex and electrical resistance in the range: 3 Ω/m (AgSISLib40) -<340 Ω/m (V1) were used to make tubular structures on knitting technology by using circular knitting machines of the type SANGIACOMO - HT1. The surface resistance of textile structures with metal threads was measured using the CROPICO 4000 Multimeter device consisting of two parallel linear electrodes, placed at a distance of 30 mm. All the geometrical parameters of the sample were measured (L = 0.03 m, D = 0.02 m and g) and electrical resistivity was calculated in [Ohm-meter]. The electrical conductivity of the textile structures was calculated with the inverse relation of the resistivity.

The conductivity values in the direction parallel to the conductive yarns in conductive, tubular textile structures made on circular knitting machines are about 70% higher than the values recorded in the direction perpendicular to the conductive yarns.

The parameter that decisively influences the conductivity level of textile structures is the linear resistance (Ω/m) of the component yarns, followed by the length of the metallic yarn per unit area of the textile structure and the thickness of the material.

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