

# STUDY OF THE CONTACT RESISTANCE OF INTERLACED STAINLESS STEEL YARNS EMBEDDED IN HYBRID WOVEN FABRICS

Simona Vasile<sup>1</sup>, Frank Deruck<sup>2</sup>, Carla Hertleer<sup>3</sup>, Alexandra De Raeve<sup>1</sup>, Thomas Ellegiers<sup>1</sup>, Gilbert De Mey<sup>4</sup>

<sup>1</sup>University College Ghent, Faculty of Science and Technology, Department of Textiles, Fashion and Wood technologies, Buchtenstraat 11, 9051 Sint-Denijs-Westrem, Belgium, corresponding author simona.vasile@hogent.be

<sup>2</sup>University College Ghent, Faculty of Science and Technology, Department of Exact Sciences, Valentin Vaerwyckweg 1, 9000 Gent

<sup>3</sup>Ghent University, Faculty of Engineering and Architecture, Department of Textiles, Technologiepark 907, 9052 Zwijnaarde, Belgium

<sup>4</sup>Ghent University, Faculty of Engineering and Architecture, Department of Electronics and Information ELIS, Technologiepark-Zwijnaarde 15, 9052 Gent

## Abstract:

*The contact resistance of two interlacing electro-conductive yarns embedded in a hybrid woven fabric will constitute a problem for electro-conductive textiles under certain circumstances. A high contact resistance can induce hotspots, while a variable contact resistance may cause malfunctioning of the components that are interconnected by the electro-conductive yarns. Moreover, the contact robustness should be preserved over time and various treatments such as washing or abrading should not alter the functioning of the electro-conductive textiles. The electrical resistance developed in the contact point of two interlacing electro-conductive yarns is the result of various factors. The influence of diameter of the electro-conductive stainless steel yarns, the weave pattern, the weft density, and the abrasion on the contact resistance was investigated. Hybrid polyester fabrics were produced according to the design of experiments (DoE) and statistical models were found that describe the variation of the contact resistance with the selected input parameters. It was concluded that the diameter of the stainless steel warp and weft yarns has a statistically significant influence on the contact resistance regardless of the weave. Weft density had a significant influence on the contact resistance but only in case of the twill fabrics. Abrasion led to an increase in contact resistance regardless of the weave pattern and the type of stainless steel yarn that was used. Finally, a combination of parameters that leads to plain and twill fabrics with low contact resistance and robust contacts is recommended.*

## Keywords:

*Electro-conductive textiles, weaving, stainless steel yarns, four point measurement, contact resistance, abrasion*

## 1. Introduction

Electro-conductive textiles are basic materials for smart textiles, and they can be used in components such as sensors, actuators, data transmission lines, or textile antenna's. To ensure good functioning, adequate interconnection between these components must be realized. Electro-conductive yarns can be used to connect various components, and they are embedded in the textile structure via various techniques such as embroidery, knitting, or weaving. In woven fabrics, electro-conductive yarns are integrated in warp and weft directions to guide electrical current through the fabric from one component to another. When electro-conductive weft and warp yarns are crossing each other, an electrical contact point is created. There are two types of resistance that the electrical signal will encounter: bulk resistance and contact resistance. Bulk resistance is the resistance of the materials along the current's path, and its values is constant [1]. Otherwise, contact resistance is a variable resistance that occurs at the interface between two contact surfaces (e.g. weft and warp yarns). Contact resistance is made up of constriction resistance and film resistance and is dependent on the contact force between the two surfaces in contact [1]. The contact point between two interlacing warp and weft yarns should be robust with a low contact resistance. Therefore, a high contact force ensures a robust contact with a low contact resistance. Furthermore, a contact with a larger

cross-sectional area will offer less resistance than a thinner, narrower contact. Film resistance occurs due to the thin layers of metal oxides and dirt that is formed on the surface of the material. Oxides have higher resistivity which requires more effort for the signal to travel through the film [1]. An uneven distribution of the contact resistance could also alter the performance of a sensor or an antenna made up of the fabric [2].

Several research groups investigated the contact resistance between two interlaced electro-conductive yarns. Banaszczyk *et al.* [3] developed a numerical method for obtaining the current distribution in a fabric consisting of exclusively conductive yarns. The authors concluded that the existence of the contact resistance disqualified woven and knitted structures as simple isotropic conductors. Furthermore, an experimental method was presented for measuring the contact resistance between two crossing yarns. Banaszczyk *et al.* [4] and Dhawan *et al.* [5] used an ordinary, direct four-point voltage and current measurement procedure to measure the contact resistance. Additionally, Banaszczyk *et al.* [6] also presented an indirect method in which an infrared thermograph of a sample was compared to its numerical model. Banaszczyk *et al.* [4, 6] and Dhawan *et al.* [5] used a yarn set up consisting of two free-hanging yarns and measured the contact resistance between the yarns. The yarns were not embedded in a woven structure, and this yarn setup does not reflect the geometry and

the mechanical situation of a woven sample [2]. Gunnarsson *et al.* [2] presented a technique for measuring the contact resistance between two multifilament silver-coated yarns embedded in plain fabrics. This technique thereby provides a means for obtaining realistic values of the contact resistance. It was reported that the electrical contacts between the warp and weft yarns were very sensitive to mechanical disturbance [2]. The contact resistance is the result of a huge number of microscopic real contacting spots created by the load between the crossing yarns. This load easily changes with sample handling leading to a change in the contact resistance. It was stated that in more or less real-life situations, the contact resistance of interlacing multifilament silver-coated yarns will vary and this variation will depend on yarn, weave, and environmental factors. A new measurement of contact resistance will, therefore, be necessary each time one wishes to make a new fabric with conductive yarns [2]. The model developed by Gunnarsson [2] assumed that the yarns made contact only at the crossing point. Nevertheless, two adjacent yarns could also make additional contacts that lead to higher overall contact resistance. This was especially the case in fabrics with high (weft) density. The results of Gunnarsson [2] strengthened the statement of Banaszczyk *et al.* that a woven fabric could not automatically be modeled as a homogeneous and isotropic sheet. The current distribution is also a factor to be considered when electro-textiles are designed [2]. Banaszczyk *et al.* [4] also studied the influence of the thin transparent oxide layer of  $\text{Cr}_2\text{O}_3$  that covers the stainless steel yarns and found that this layer has a crucial influence on the contact resistance. It was stated that, for very low currents, the contact resistance is linear and it is influenced by both the pressure on the junction and the thickness of the oxide layer. The junction will heat up when the current increases, the oxide starts to evaporate, and it introduces a nonlinearity into the contact resistance curve. Once the oxide layer for a certain current range is burned out, the contact resistance curve in that range remains linear [4].

In strain sensor applications, knitted structures are preferred to woven fabrics, which are generally characterized by good dimensional stability, poor skin contact, and limited elastic recovery. Related research [7-10] studied the contacts between electro-conductive yarns embedded in knitted fabrics. Unlike in woven hybrid fabrics, in knitted fabrics, contacts appear between two consecutive conductive loops and not only at the intersection of weft and warp yarns. Atalay *et al.* [7] developed knitted strain sensors with silver-coated polymeric yarn as sensing element. In this research, the effect of contact pressure on the electrical resistance as well as sensor characteristics

was studied and a strong relationship was found between base fabric parameters and sensor parameters. Atalay *et al.* [7] concluded that it is possible to manipulate the sensing properties of knitted sensors and the sensor response may be engineered by varying the production parameters applied to specific designs [8]. Zhang *et al.* [9] created knitted strain sensors by using stainless steel and carbon yarns and identified that the contacting electrical resistance between overlapped fibers is the primary factor in the sensing mechanism. Li *et al.* [10] also modeled the resistance of conductive knitted fabrics by superposition of the length-related resistance and contact resistance and established relationships between the resistance, tensile force, fabric length, and width.

Monofilament silver clad copper yarn [11] and multifilament stainless steel yarns [12] were used in the Wintex project [13]. The aim of the project was to identify parameters that lead to a low electrical resistance and temperature in the contact point of two electro-conductive yarns embedded in hybrid woven fabrics. Some parameters with potential influence on the contact resistance were investigated [14, 15].

## 2. Experimental

In this study, the influence of selected factors (diameter of weft and warp stainless steel yarns, weave pattern, weft density, and abrasion) on the contact resistance was analyzed. This paper presents factors that have a statistically significant influence on the contact resistance of two interlaced stainless steel yarns.

### 2.1 Materials

Commercially available Bekinox<sup>®</sup>VN stainless steel yarns [12] were used, and hybrid polyester fabrics were woven on a rapier loom. The characteristics of the VN12.2, VN12.3, and VN12.4 yarns used in this study are shown in Table 1. As it can be seen in Table 1, each yarn was given five types of codes which was separated by a slash. Each code from left to right consequently represents (1) the diameter of the individual filaments, for example, 12  $\mu\text{m}$ ; (2) the amount of plies (multifilament bundles) twisted together, which ranges from 2 to 4; (3) the amount of filaments used to make a pile (275 filaments); (4) the number of torsions per meter and the twist direction (e.g., S or Z); (5) the composition of the filaments, for example, AISI 316 L stainless steel. Stainless steel is an alloy of iron: chromium

**Table 1.** Characteristics of the Bekinox<sup>®</sup>VN stainless steel yarns

	Stainless steel Bekinox <sup>®</sup> VN yarns		
	VN12/2x275/175 S/316L	VN12/3.x275/175 S/316L	VN12/4x275/100S/316L
Yarn abbreviation	VN12.2	VN12.3	VN12.4
Diameter of one filament ( $\mu\text{m}$ )	12	12	12
Total yarn diameter ( $\mu\text{m}$ )	460	643	775
Number of filaments	275	275	275
Number of plies	2	3	4
Torsion /m	175 S	175 S	100 S
Linear resistance R ( $\Omega/\text{m}$ )	14.41	9.8	7.5

(16-18% by weight), nickel (10–14%), molybdenum (2–3%), manganese (2%), carbon (<0.03%), and iron (the balance) [14]. The presence of chromium makes the steel stainless. If enough chromium is present in the alloy (more than 12.5%), the oxidation of chromium will be faster than the oxidation of iron. The oxidation product Cr<sub>2</sub>O<sub>3</sub> will form a dense inert layer that prevents oxidation of the iron [14].

Multifilament polyester yarns of 1,100 dtex (130 torsions/m) and 1,100 dtex (60 torsions/m) were used as warp and weft yarns, respectively. The stainless steel yarns were additionally inserted in warp and weft directions (Figure 1) and hybrid fabrics with a warp density of 18 yarns/cm were produced.

The plain and twill fabrics (Figure 2a and 2b) were woven according to the design of experiments (DoE).

A statistical software JMP 11 [16] was used to generate the DoE. Three input parameters were considered in the design: weft density (8 pics/cm or 10 pics/cm), type of electro-conductive warp yarn, and type of electro-conductive weft yarn (e.g. VN12.2, VN12.3, VN12.4). The combination of the input parameters led to 18 fabrics for each weave with the fabric ID (generated by the statistical software) as shown in Table 2. For the ease of results interpretation, the fabrics were not arranged by their ID but according to the weft density, starting with the lowest weft density.

**2.2 Methods**

The contact resistance of two interlaced stainless steel yarns was measured before and after abrasion.

**2.2.1 Contact resistance**

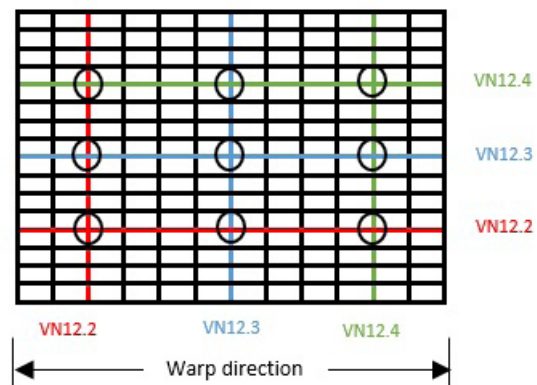
The contact resistance was assessed with a four-point method. As shown in Figure 3, a current I (A) was sent through two interlacing stainless steel yarns and the voltage drop (V) was measured by connecting the other ends of the yarn to a voltmeter. In this situation, the effect of the clamps, yarns, and wires was eliminated and the contact resistance is accurately measured. A TTI Power supply EL 301 R [17] was used to apply an electrical current I (A), and a Fluke 87 V True RMS multimeter [18] was used to measure the voltage V (V). The electrical resistance R (Ω) was calculated from Ohm’s law:  $I = V/R$ .

**2.2.2 Abrasion**

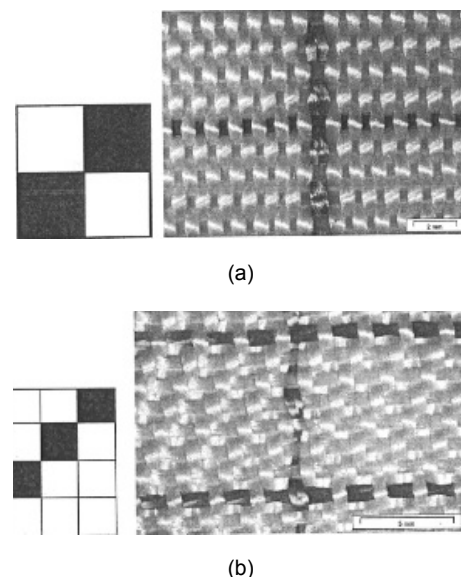
The hybrid fabrics were subjected to abrasion tests and the contact resistance was measured again after 20,000 abrasion cycles in order to assess the robustness of the electrical contacts. This test was performed by means of the Martindale method (Figure 4), in compliance with the ISO 12947-2 standard [19].

**3. Results and discussions**

A current of up to 0.7 A was applied to the contact point, depending on the type of the two interlaced stainless steel



**Figure 1.** Schematic representation of hybrid woven fabric with nine contact points between stainless steel yarns VN12.2, VN12.3, and VN12.4 inserted in weft and warp directions



**Figure 2.** Schematic representation and picture of hybrid fabric with (a) plain weave and (b) twill 3/1 weave [14]

**Table 2.** Experimental design for hybrid plain and twill fabrics

Fabric ID	Weft density (pics/cm)	Stainless steel warp yarn ID	Stainless steel weft yarn ID
13	8	VN12.2	VN12.2
15	8	VN12.2	VN12.3
14	8	VN12.2	VN12.4
16	8	VN12.3	VN12.2
7	8	VN12.3	VN12.3
12	8	VN12.3	VN12.4
9	8	VN12.4	VN12.2
8	8	VN12.4	VN12.3
4	8	VN12.4	VN12.4
17	10	VN12.2	VN12.2
5	10	VN12.2	VN12.3
10	10	VN12.2	VN12.4
2	10	VN12.3	VN12.2
1	10	VN12.3	VN12.3
6	10	VN12.3	VN12.4
18	10	VN12.4	VN12.2
11	10	VN12.4	VN12.3
3	10	VN12.4	VN12.4

yarns, and the contact resistance was calculated. For all 18 fabrics, the values of the contact resistance used in the following calculations correspond to a current of 0.25 A. These values are directly calculated or deducted by extrapolation from the best-fitted curve. In Figure 5, an example is given for plain fabric ID13 in which the contact resistance (2.28 Ω) corresponding to a current of 0.25 A was deducted by extrapolation.

**3.1 Contact resistance between two stainless steel yarns embedded in plain fabrics**

The values of the contact resistance measured between two interlacing stainless steel yarns are shown in Figure 6.

The contact resistance *before abrasion* varied between 0.4 Ω for fabric ID3 (warp and weft VN12.4, weft density 10 pics/cm) and 2.2 Ω for fabric ID13 (both warp and weft VN12.2, weft density 8 pics/cm). The low value of the contact resistance results from a large contact surface between the two thick interlaced VN12.4 yarns and also from a high weft density that

ensured a tighter contact between the yarns. Conversely, the combination of fine warp and weft yarns (VN12.2) and a looser structure with a lower weft density led to the highest contact resistance.

The JMP software was used for statistical analysis of the results. For a level of significance  $\alpha = 0.05$ , the diameters of the warp and weft yarns (Figure 7a) were found to be significant factors ( $p = 0.0445$  and  $p = 0.0368$ , respectively): the thicker the yarns, the lower is the contact resistance. Within the range 8–10 pics/cm, no further interactions were found and weft density was not found to be a significant factor. The random distribution of the residuals (not displayed) indicates that the model is good and the rather low coefficient of determination ( $R^2 = 0.56$ ) may be the result of experimental noise and random effects.

*After abrasion*, the contact resistance increased for almost all types of contacts except for the following four: fabric ID1 (warp and weft VN12.3/ 10 pics/cm), fabric ID10 (VN12.2/ VN12.4/ 10 pics/cm), fabric ID14 (warp VN12.2/ weft VN12.4/ 8 pics/

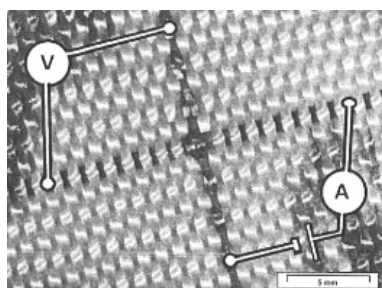


Figure 3 Schematic representation of the four-point method [14]



Figure 4 Martindale tester

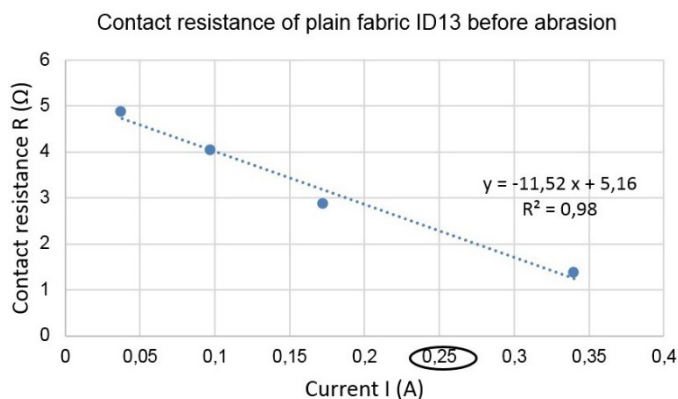


Figure 5 Contact resistance of plain fabric ID13 before abrasion

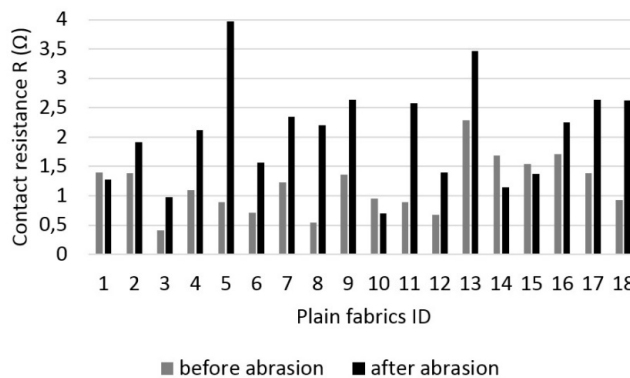


Figure 6 Contact resistance (for 0.25 A) for hybrid plain fabrics before and after abrasion

Summary of Fit					
RSquare					0,560662
RSquare Adj					0,425481
Root Mean Square Error					0,359633
Mean of Response					1,171111
Observations (or Sum Wgts)					18
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Warp	2	2	1,0323631	3,9910	0,0445*
Weft	2	2	1,1133181	4,3040	0,0368*

(a)

Summary of Fit					
RSquare					0,448753
RSquare Adj					0,330628
Root Mean Square Error					0,704548
Mean of Response					2,064667
Observations (or Sum Wgts)					18
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Weft(VN12.4-VN12.3&VN12.2)	1	1	4,9885223	10,0497	0,0068*
Warp	2	2	0,6687790	0,6736	0,5256

(b)

Figure 7 Statistical analysis for plain fabrics parameters with significant influence on contact resistance: (a) before abrasion and (b) after abrasion

cm), and fabric ID15 (VN12.2/ VN12.3/ 8 pics/cm) as shown in Figure 6. A minimum value (0.7 Ω) was registered for fabric ID10 (warp VN 12.2, weft VN12.4, weft density 10 pics/cm), and a maximum value (3.9 Ω) for fabric ID5 (warp VN12.2, weft VN12.3, weft density 10 pics/cm). It was expected that abrasion would disturb the contact and lead to an increase in the contact resistance. The results are in agreement with the work of Gunnarsson *et al.* [2] who also noticed the modification of the contact resistance during fabric handling and testing. Also Banaszczyk *et al.* [3] stated that contact resistance will change over time, after handling and especially washing the textiles. For a level of significance of  $\alpha = 0.05$ , the warp diameter had an influence on the contact resistance, but it was not statistically significant (Figure 7b). However, the weft diameter had a significant influence ( $p = 0.0068$ ) on the contact resistance of the plain fabrics subjected to abrasion. The rather low coefficient of determination ( $R^2 = 0.44$ ) of the model may be the result of measurement errors and random effects. A second statistical analysis was performed and abrasion was added as fourth input parameter with two levels of variation: 0 abrasion cycles and 20,000 abrasion cycles. A coefficient of determination  $R^2 = 0.53$  was found for the four-parameter statistical model (Figure 8a). For a level of significance of  $\alpha = 0.05$ , the abrasion ( $p = 0.0007$ ) and the weft diameter ( $p = 0.0010$ ) had a significant influence on the contact resistance of the considered fabrics. The statistical model indicated that the stainless steel yarn VN12.4 should be used as weft yarn to produce plain fabrics with low contact resistance and a robust contact point which is not affected by abrasion. In that case, similar values of contact resistance before and after abrasion were obtained, as it can be observed in Figure 8b.

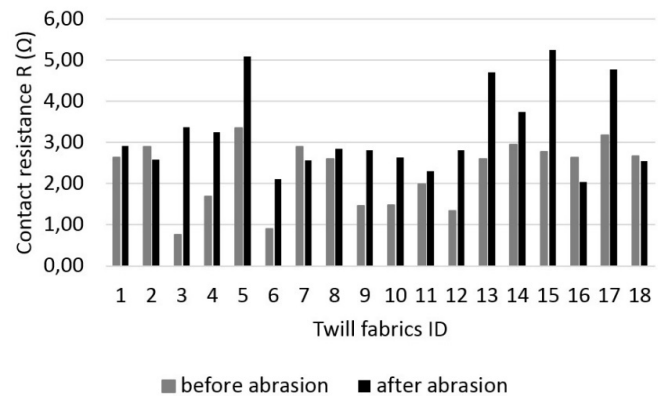
**3.2 Contact resistance between two stainless steel yarns embedded in twill fabrics**

The values of the contact resistance measured between two interlacing stainless steel yarns embedded in twill fabrics are shown in Figure 9.

Similar to the plain fabrics, a minimum contact resistance value (0.77 Ω) was registered for fabric ID3, which consists of thick weft and warp stainless steel yarns and have a high weft density. The highest value (3.36 Ω) was observed for

fabric ID5 (weft yarn VN12.2, weft yarn VN12.3, weft density 10 pics/cm). For a level of significance of  $\alpha = 0.05$ , the warp and weft yarns ( $p = 0.0086$  and  $p = 0.0002$ , respectively) as well as the interaction between weft density and weft diameter ( $p = 0.0291$ ) were statistically significant factors. An acceptable model with a coefficient of determination  $R^2 = 0.74$  was obtained (Figure 10a). The random distribution of the residuals indicated that residual variation is due to noise effects. *After abrasion*, the contact resistance increased for almost all contacts except four cases: fabric ID2 (warp VN12.3, weft VN12.2, 10 pics/cm), fabric ID7 (VN12.3 warp, VN12.3 weft, 8 pics/cm), fabric ID16 (warp VN12.3, weft VN12.2, 8 pics/cm), and fabric ID18 (VN12.4 warp, VN12.2 weft, 10 pics/cm). The differences between the contact resistance of these four fabrics (before and after abrasion) were, however, small, and they can be the result of some measurement errors. For a level of significance of  $\alpha = 0.05$ , the effects of warp and weft diameter ( $p < 0.0001$  and  $p = 0.0054$ , respectively) as well as their interaction ( $p=0.0003$ ) were statistically significant, as shown in Figure 10b. A statistical model with a coefficient of determination  $R^2 = 0.86$  was obtained.

Similar to plain fabrics, a four-parameter design was generated by the JMP software and abrasion was added as a fourth input parameter. A coefficient of determination ( $R^2$ ) of 0.8 was found with five significant parameters. For a level of significance of  $\alpha = 0.05$ , abrasion had a significant influence ( $p < 0.0001$ )



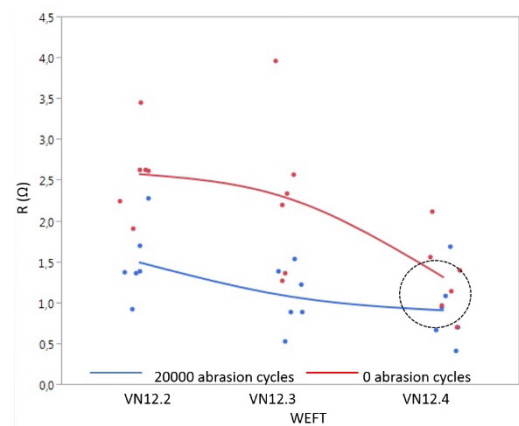
**Figure 9** Contact resistance (for 0.25 A) for hybrid twill fabrics before and after abrasion

Summary of Fit	
RSquare	0.539432
RSquare Adj	0.496254
Root Mean Square Error	0.583055
Mean of Response	1,617,889
Observations (or Sum Wgts)	36

Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	1,493,458.3	0,103,071	14,49	<.0001*
abrasion[0]	-0,385,083	0,103,071	-3,74	0,0007*
weft{VN12.4-VN12.3&VN12.2}	-0,373,292	0,103,071	-3,62	0,0010*
abrasion[0]*weft{VN12.4-VN12.3&VN12.2}	0,185,0833	0,103,071	1,80	0,0820

(a)



(b)

**Figure 8** Four-parameter statistical model for plain fabrics: (a) parameters with significant influence on contact resistance and (b) combination of input parameters that lead to a robust contact

on the contact resistance (Figure 11a). The diameter of warp and weft yarns had an significant negative influence ( $p = 0.001$ ). Significant interactions effects were observed between abrasion/warp yarns ( $p = 0.0106$ ) and weft density/weft yarns ( $p = 0.0215$ ). In Figure 11b, combinations of parameters that lead to twill fabrics with robust contacts with a low contact resistance are shown. For instance, fabrics that preserve their contact resistance are made with weft yarns VN12.3, weft density of 8 pics/cm, and warp yarns VN12.3 or VN12.4. Similarly, for twill fabrics with a high weft density (10 pics/cm), the warp yarns VN12.3 and VN12.4 are recommended either in combination with weft yarn VN12.2 or with VN12.3.

### 4. CONCLUSIONS

- The contact resistance corresponding to the interlacing point of two stainless steel yarns embedded in hybrid fabrics in weft and warp directions was studied. Hybrid fabrics were produced according to the DoE with the following input parameters: diameter of the stainless-steel yarns (three types), weave pattern (plain and twill), and weft density (two density levels). Parameters with statistically significant influence on the contact resistance were identified for each weave pattern, before and after abrasion.
- The statistical models were differentiated per weave pattern. No general statistical model that is valid for both plain and twill fabrics was found. Nevertheless, the diameter of the stainless

steel yarns was found to be a significant factor regardless of the weave pattern: yarns with a large diameter are recommended when a low contact resistance is desired.

- The weft density influences the tightness of the woven structure, and it was found to be a significant parameter for twill fabrics in interaction with the weft yarn.
- The robustness of the given electrical contacts was affected by abrasion. The contact resistance increased after 20,000 abrasion cycles, for the majority of the given contacts. The diameter of the warp and weft yarns had also a significant influence on the contact resistance between two stainless steel yarns embedded in plain fabrics subjected to abrasion. Warp and weft electro-conductive yarns as well as their interaction were found significant, in case of twill fabrics subjected to abrasion.
- The statistical models found recommend using weft yarns VN12.4 for production of plain fabrics with robust contacts (unaffected by abrasion) and low-value contact resistance. For the given parameters, various combinations that lead to twill fabrics with robust contacts are possible.
- Further research should confirm the reproducibility of these results. Nevertheless, it can be concluded that robust electrical contacts can be achieved, for each weave, by appropriately selecting the diameter of the electro-conductive stainless steel yarns and the weft density of the fabric.

Summary of Fit	
RSquare	0,743909
RSquare Adj	0,689033
Root Mean Square Error	0,444969
Mean of Response	2,267661
Observations (or Sum Wgts)	18

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Warp(VN12.4&VN12.3-VN12.2)	1	1	1,8482856	9,3349	0,0086*
Weft(VN12.4-VN12.2&VN12.3)	1	1	5,0341149	25,4252	0,0002*
Density*Weft(VN12.4-VN12.2&VN12.3)	1	1	1,1697871	5,9081	0,0291*

(a)

Summary of Fit	
RSquare	0,867791
RSquare Adj	0,839461
Root Mean Square Error	0,414175
Mean of Response	3,239167
Observations (or Sum Wgts)	18

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Warp(VN12.3&VN12.4-VN12.2)	1	1	6,4201389	37,4263	<,0001*
Weft(VN12.4-VN12.2&VN12.3)	1	1	1,8585920	10,8347	0,0054*
Warp(VN12.3&VN12.4-VN12.2)*Weft(VN12.4-VN12.2&VN12.3)	1	1	3,7922580	22,1070	0,0003*

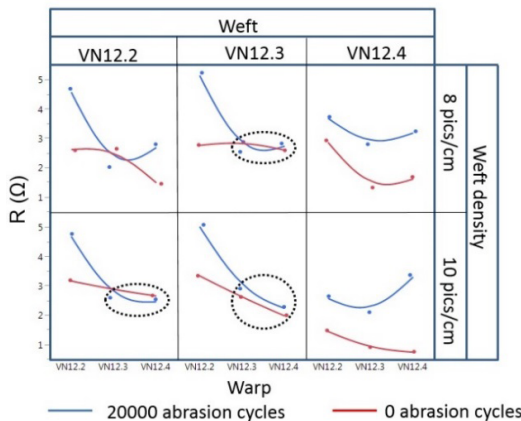
(b)

Figure 10 Statistical analysis for twill fabrics parameters with significant influence on contact resistance: (a) before abrasion and (b) after abrasion

Summary of Fit	
RSquare	0,805952
RSquare Adj	0,748457
Root Mean Square Error	0,51903
Mean of Response	2,753414
Observations (or Sum Wgts)	36

Parameter Estimates					
Term	Estimate	Std Error	t Ratio	Prob> t	
Intercept	4,1608047	0,831487	5,00	<,0001*	
abrasion[0]	-0,631697	0,096716	-6,53	<,0001*	
weft density	-0,150719	0,091752	-1,64	0,1120	
warp(VN12.3&VN12.4-VN12.2)	-0,527914	0,097318	-5,42	<,0001*	
weft(VN12.4-VN12.2&VN12.3)	-0,439173	0,097318	-4,51	0,0001*	
abrasion[0]*warp(VN12.3&VN12.4-VN12.2)	0,2520604	0,091752	2,75	0,0106*	
abrasion[0]*weft(VN12.4-VN12.2&VN12.3)	-0,185773	0,091752	-2,02	0,0529	
(weft density-9)*weft(VN12.4-VN12.2&VN12.3)	-0,223898	0,091752	-2,44	0,0215*	
warp(VN12.3&VN12.4-VN12.2)*weft(VN12.4-VN12.2&VN12.3)	0,1920766	0,097318	1,97	0,0587	

(a)



(b)

Figure 11 Four-parameter statistical model for twill fabrics: (a) parameters with significant influence on contact resistance and (b) combination of input parameters that lead to a robust contact

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