Predicting conducting yarn failure in woven electronic textiles

Hans de Vries a,*, Ron Peerlings b

a Philips Research, High Tech Campus 34-6, 5656AE Eindhoven, The Netherlands
b Department of Mechanical Engineering, Eindhoven University of Technology, PO Box 513, 5600MB Eindhoven, The Netherlands

ABSTRACT

Smart, electronic textiles are often exposed to tensile stress which can lead to fracture of the interwoven conducting yarns. In this study, a model is proposed to relate the extensibility of the conducting yarns to the weaving pattern of the textile – in particular to the thickness and pitch of the textile yarns. The model is validated by simultaneous mechanical and electrical tests on bare yarns extracted from several textiles. The results show that mechanical failure precedes electrical failure. Thus, a lower and conservative bound for electrical failure can be obtained from the extensibility prediction as a function of the structure of the weave.

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1. Introduction

Integration of electronic functionality in textiles has paved the way for novel and widely different application areas, ranging from light-therapy to signage and decoration [1–5]. In case of monitoring physiological functions or applying medical therapy, the advantage of using textile-based devices is their comfort of wearing. In the second place, because of the textile’s compliance and breathability, it is possible to carry out such measurements and therapy close to the skin. Several fabrication methods are used, among which weaving, stitching and embroidery of conducting yarns in or on the fabric have gained much attention. In principle, standard manufacturing methods are used to incorporate the conducting yarn in the textile. In the case of stitching the yarn is added by guiding it with a needle through the textile. It is held in position by a counter thread that can be either conducting or not. In the embroidery process the yarn is fixed on the surface of the textile by a separate thread. In these two methods the conducting yarn is thus applied after the textile has been made, or even after the product has received its actual shape. This is quite different in weaving on a loom, where the conducting yarn is woven simultaneously with the entire textile. The yarn thus follows the weave pattern. Subsequently, rigid components such as light emitting diodes or sensors are mounted onto the textile and electrical contact is made with the conducting yarns by soldering or applying conducting adhesives. For further details on the technologies and applications, we refer to the abovementioned publications.

Since textiles are meant to be worn, washed, and stored, they will be bent, folded, etc., and thus specific mechanical loads are invoked in the above-mentioned applications, apart from the usual environmental stresses. For instance, textile fibers can be exposed to bending radii of less than 1 mm [6], forces up to a few thousands Newton per meter [7], and strains of 20% [8]. Therefore specific failure modes may influence the reliability of devices based on the so-called electronic-textile technology. In particular breaking failure modes may influence the reliability of devices based on the so-called electronic-textile technology. In particular breaking of the attachment between component and conducting yarn requires attention, as the materials used for this purpose (e.g. solder materials) are generally soft and sensitive to stress. Special structures have been designed which protect the attachment against excessive loading. In the electronics industry globtop and underfill are frequently used to reinforce the components’ attachment to the substrate. On flexible foil substrates this is often done in combination with conductive adhesive interconnections [9]. Also for textile substrates protective measures have been proposed, such as globtop to strengthen the adhesive attachment of LEDs [10], or an intermediate textile layer to shield the conductive yarn from bending over a sharp edge [11].

In this contribution, however, we focus on the reliability of the conductive yarns – and in particular on a class of yarns which are composed of a bundle of metallic filaments. We consider a woven textile with embedded conducting yarns and aim to understand how the electrical and mechanical failure of the conducting yarns depends on the parameters of the textile, i.e. the thickness and spacing of the textile yarns. Prior experimental results on free-

* Corresponding author.
E-mail address: jw.c.de.vries@philips.com (H. de Vries).
standing conducting yarns show that the onset of mechanical failure precedes their electrical failure. It may thus be possible to make a – conservative – prediction of the electrical failure by means of a suitable model that describes mechanical failure. Such a model would be useful for designers as it would allow them to select conductive yarns and weaves which guarantee reliability a priori – i.e. without the need for prototyping and (electrical) measurement. In order to systematically address this question, conductive yarns have been extracted from different types of woven electronic textile and subjected to tensile tests in which also their resistance is measured. This allows us to simultaneously measure the electrical and mechanical response of the individual yarns, without any influence of the surrounding textile. Based on earlier work on the mechanical modeling of the conducting yarns, a simple model for yarn failure is formulated, as a function of the yarn thickness and spacing of the textile substrate. The trends predicted by the model are confronted with the measured mechanical and electrical data in order to establish the validity of the predictions.

2. Experiments

To be able to study the extensibility of conducting yarns that have been deformed by weaving them into textiles, single conducting yarns were carefully extracted from the woven fabric by cutting away the textile yarns surrounding them. A number of textiles differing in two main characteristics, but containing identical conducting yarns, were used for the tests. These characteristics are the “dtex” – the mass in grams of 10,000 m of the textile thread – and the “picks per centimeter” – the number of weft threads per centimeter. Table 1 shows these parameters for the different textiles considered. Fig. 1 shows a typical textile with woven conducting yarns; in Fig. 2a de-engineered yarn (i.e. after being extracted from the textile) with float is shown. A float is a not-woven part of the conducting yarn lying on top of the fabric to facilitate electrical contact with components.

The conductive yarn is Elektrisola litze [12] yarn that consists of 20 silver plated copper filaments with a diameter of 0.04 mm, each wrapped with a twist of approximately 240/m. The non-conducting multifilament threads of the textile are made of polyester (PES spun fiber yarn). The textile samples were made by the Institute for Special Textiles and Flexible Materials (TITV Greiz, Germany).

Tensile tests were done on the de-engineered conducting yarns while simultaneously measuring their electrical resistance. The tensile tests were carried out on an Instron 5566 tensile tester. The yarns were stretched at a rate of 1.7–2.1 × 10\(^{-3}\)/s until electrical failure was observed. In order to prevent slipping of the samples from the clamps, dummy pieces of printed circuit board were laminated with adhesive tape to the bare yarns. In addition, in order to establish the relevance of the single-yarn measurements, pieces of textile with integrated conducting yarns were tested. The four-point resistance measurements were done with an Agilent 34970A-datalogger equipped with a 34901A-multiplexer. Output signals monitoring the load and the displacement of the tensile tester were also connected to the multiplexer unit. In this way all relevant parameters could be simultaneously recorded. Data logging was done with an interval of 0.5 s. Four yarns of each of the above mentioned types (A–D) were tested in this way.

3. Model

It has previously been established by de Boer [13] that the extensibility of the conductive yarns extracted from the textile samples is lower than that of the unwoven conducting yarns. This loss of extensibility is due to the plastic deformation which the yarns undergo during weaving. The conducting yarns, which are predominantly in warp direction (see Fig. 1) are bent around the weft textile yarns during weaving and this induces plastic (bending) strain in the conducting yarns. Part of their ductility is thus lost in fabrication and the remaining plastic strain which they can still undergo is reduced. One could argue that the spring-like shape which the conducting yarns adopt upon weaving actually enhances their extensibility, as they first need to be straightened again before being stretched. But for realistic textile yarn thicknesses and spacings it was found that this effect is secondary to the loss of ductility by bending strains induced during weaving [13].

A simple model for the effect of bending strains due to weaving may be obtained by assuming that the individual filaments in the conducting yarn adopt a harmonic shape:

\[
y(x) = A \cos \frac{2\pi x}{\lambda}
\]  

(1)

where \(x\) is the coordinate along the length of the filament and \(y\) denotes its out-of-plane displacement due to the weaving pattern; \(A\) and \(\lambda\) denote the amplitude and the wavelength of the pattern, respectively. The above expression neglects the spiraling shape of the filament within the conductive yarn. This is justified since the wavelength of the weave (\(\lambda\)) is much smaller than that associated with the internal twist in the yarn – and the plastic strain induced by it thus much larger.

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Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Dtex (D)</th>
<th>Picks/cm (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>B</td>
<td>145</td>
<td>28</td>
</tr>
<tr>
<td>C</td>
<td>167</td>
<td>22.8</td>
</tr>
<tr>
<td>D</td>
<td>145</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Fig. 1. Textile (circa 100×100 mm\(^2\)) with conducting yarns and detail showing floats. Warp is in the horizontal direction. Scale bars are shown.

Fig. 2. Bare conducting yarn with float, prepared from woven textile. Scale bar is shown.
Differentiating Eq. (1) twice shows that the curvature of the filament introduced by weaving scales with $A/d^2$. We furthermore assume that the filament's cross section remains circular and that its material deforms rigid-plastically under pure bending. The bending strain is proportional to the curvature of the yarn, so for a filament of diameter $d$ the plastic strain introduced due to the bending scales with $Ad/d^2$. Now, in order to make contact with the textile parameters as given in Table 1, let us assume that the weaving pattern amplitude scales with the square root of the dtex, i.e. $A \propto \sqrt{D}$, where $D$ denotes the dtex. The wavelength, on the other hand, is inversely proportional to the number of picks per cm, $p$, i.e. $\lambda \propto 1/p$. The plastic strain introduced by weaving is thus expected to be proportional to $p^2 d / \sqrt{D}$.

As a consequence of the plastic deformation of the filaments of the conducting yarn during weaving, their remaining extensibility is reduced. The unwoven yarns fail mechanically at a certain strain, which we denote by $E_0$, due to excessive plastic deformation of their filaments. In weaving these yarns into the textile, we already spend part of their plastic deformability (ductility); the woven yarn thus has an extensibility $E_M$ which is lower than that of the unwoven yarn: $E_M < E_0$. It is reasonable to assume that the loss of ductility scales with the plastic deformation introduced by weaving, i.e. with $p^2 d / \sqrt{D}$, so that we have

$$E_M = E_0 - \alpha p^2 d / \sqrt{D}$$

(2)

where $\alpha$ is a proportionality constant, in which we have absorbed the filament diameter $d$, which is constant in our experiments. If the textile characteristics are given in SI-units, the unit of $\alpha$ is $m^2 / (m / kg)^{1/2}$.

For a more comprehensive version of the model, including also the competing spring-effect, we refer to de Boer [13]. For our present purpose, however, the above simple relationship suffices. It allows us to predict the effect of the textiles' characteristics $D$ and $p$ on the extensibility of the embedded conducting yarn once the constants $E_0$ and $\alpha$ have been calibrated on experimental data.

4. Results and discussion

Fig. 3 shows selected test results, i.e. the electrical and mechanical response of a single conducting yarn and a single textile sample as a function of the applied strain (relative elongation). This data is qualitatively representative for all measurements, but the characteristic strains at which a change in behavior is observed depends on the weaving pattern. Some scatter is also observed between nominally identically samples (see Table 2).

One can observe differences between the results for the textile and the bare conducting yarn. For the bare yarn the force increases until about 5 N with the resistance remaining constant. At about 4% elongation the force becomes irregular and begins to decrease while more and more filaments break. Then as the force decreases further, the resistance begins to increase gradually. However, the increase does not exceed a factor of three even at 30% elongation and very small forces of 0.1 N. Complete electrical failure, i.e. a dramatic increase of the resistance, occurs at a strain in the range 15–40% (not visible in the diagram). In the textile, the resistance remains nearly constant until around 10–12% strain, and then begins to increase gradually until about 18% elongation. At this point the textile begins to tear and the resistance suddenly increases sharply by more than an order of magnitude.

These two observations, and in particular the differences between them, may be explained as follows. In a free-standing conducting yarn, near the peak force, the filaments break randomly at various locations along the length of the yarn. One can see this failure mode in the pictures in Fig. 4. Upon further extension of the yarn, the broken filaments slide along each other and thus gradually lose electrical contact. In contrast, the filaments of the conducting yarn that is woven into a textile are tightly squeezed together. Stretching the textile also causes the filaments to break at different places, but conductive paths continue to exist. When – at ~18% elongation in the example of Fig. 3 – the textile tears, the yarn is pulled apart at that location, resulting in a sudden, complete loss of conductivity.

The above implies that electrical failure is likely to occur earlier, i.e. at a smaller extension, in a free-standing, de-engineered conducting yarn than in the same yarn which is still embedded in the textile: depending on the weaving pattern the surrounding textile may stabilize the loss of electrical contact to various degrees, but it is unlikely to promote electrical failure. By studying the bare conducting yarn we are thus considering the worst case scenario, in which the textile does not constrain the yarn at all. The diagram of Fig. 3 furthermore suggests that mechanical failure (the peak force, say) of the bare yarn occurs before the onset of electrical failure – an observation which we will verify for the other textile types below.

In order to investigate the effect of the pre-deformation of the conducting yarns caused by the weaving process, and to relate this to the performance in the force–elongation tests, criteria are needed to call a failure. We have selected the absolute maximum in the force and a 15 m$\Omega$ increase of the resistance as failure criteria. The same analyses were done using the first local maximum in the force and resistance increases of 10 and 20 m$\Omega$, but this did not significantly affect the result. The resistance criterion used corresponds to 5% of the initial value of about 300 m$\Omega$.

In Table 2 the relevant characteristics of the used yarns and the factor $p^2 / \sqrt{D}$ (see Eq. (2)) are listed together with the strain at the onset of failure according to the criteria that were defined above. The relative extension at which the mechanical (force) criterion is reached is denoted $E_M$ and that at which electrical failure occurs $E_p$. Listed are the average values per sample type ($\mu$) and the standard deviation ($\sigma$). The averages $E_M$ are clearly lower than the average $E_p$, but we also find a large degree of variability for all sample types.

Fig. 6 shows the extensibility of the conducting yarn according to the electrical criterion, $E_p$, versus that according to the mechanical criterion, $E_M$, at the level of individual samples. Different markers have been used to indicate the four different sample types. All of the data points are above the line $E_p = E_M$ and we can thus conclude that mechanical failure preceded electrical failure for every tested sample. The mechanical measurement thus issues an earlier warning for failure than the simultaneously executed electrical measurement.

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The mechanical failure data of Table 2 has been fitted with Eq. (2); the result is shown in Fig. 6 by the dashed line, together with the average $E_M$ and $E_E$ (and error bars) per sample type. The fit results in parameter values of $E_0 = 0.16, \alpha = 3.9 \times 10^{-6} \text{m}^2(\text{kg/m})^{1/2}$ with a regression coefficient of $r^2 = 0.97$. The fitted value for $E_0$ is in reasonable agreement with tensile tests on unwoven conducting yarns, which failed at an extension of about 20% as reported elsewhere [13].

5. Conclusions

For the woven electronic textiles considered in this study, our main conclusions are as follows.

1. Bare conductive yarns taken from the textile fail electrically at a strain which is lower than when they are still embedded in the textile.
2. A mechanical test on the bare conducting yarn gives a lower bound for the electrical failure strain of the yarn – and thus also of the textile.
3. This lower bound may be predicted as a function of the dtex and number of picks/cm of the weave by a simple model (Eq. (2)).

It is worth noting that the lower bound given by the model may be quite conservative. Even for the bare conducting yarn, Fig. 6 shows that it underestimates the extensibility until electrical failure by roughly 25%. And depending on the constraint exerted by the textile, this gap may be significantly larger for the conducting yarn embedded in textile – see Fig. 3. On the other hand, significant damage may be induced in the yarn beyond the mechanical failure strain. Even if this does not immediately result in electrical failure in the monotonic, quasi-static loading conditions considered here, it may well affect a product’s reliability under repeated loading. In other words: one cannot conclude that a smart textile is intact because the electrical conductivity is; the conducting yarns may already be damaged. Our conservative model based on mechanical failure therefore provides valuable guidance to designers of electronic textile products in selecting the appropriate conducting yarns and weaving patterns.

We have limited ourselves in this study merely to characterizing failure of the conducting yarn at the yarn level. Future work may be aimed at developing a deeper understanding of how failure of the individual filaments affects the resistance and mechanical integrity of the yarn – even for an unwoven yarn. Such understanding, reflected in a simple model in the spirit of the present paper, might allow one to predict the parameters $E_0$ and $\alpha$ in Eq. (2), rather than having to fit them to experiments. It might furthermore inspire novel designs of conducting yarns, with a higher extensibility and/or a better robustness against weaving. Developing such a model, however, requires a more detailed experimental study of the failure of individual, de-engineered filaments, as well as of the contact (mechanical and electrical) between individual filaments, since it is the interplay between these phenomena which governs failure at the yarn level – Fig. 4.

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