Non-destructive X-ray examination of weft knitted wire structures

M Obermann1, M Ellouz2, S Aumann1, Y Martens2, P Bartelt2, M Klöcker2, T Kordisch2, A Ehrmann2,3 and M O Weber1

1 Niederrhein University of Applied Sciences, Faculty of Textile and Clothing Technology, Mönchengladbach, Germany
2 Bielefeld University of Applied Sciences, Faculty of Engineering and Mathematics, Bielefeld, Germany

E-mail: andrea.ehrmann@fh-bielefeld.de

Abstract. Conductive yarns or wires are often integrated in smart textiles to enable data or energy transmission. In woven fabrics, these conductive parts are fixed at defined positions and thus protected from external loads. Knitted fabrics, however, have relatively loose structures, resulting in higher impacts of possible mechanical forces on the individual yarns. Hence, metallic wires with smaller diameters in particular are prone to break when integrated in knitted fabrics. In a recent project, wires of various materials including copper, silver and nickel with diameters varying between 0.05 mm and 0.23 mm were knitted in combination with textile yarns. Hand flat knitting machines of appropriate gauges were used to produce different structures. On these samples, non-destructive examinations, using an industrial X-ray system Seifert x|cube (225 kV) equipped with a minifocus X-ray tube, were carried out, directly after knitting as well as after different mechanical treatments (tensile, burst, and washing tests). In this way, structural changes of the stitch geometry could be visualized before failure. In this paper, the loop geometries in the knitted fabrics are depicted depending on knitted structures, wire properties and the applied mechanical load. Consequently, it is shown which metallic wires and yarns are most suitable to be integrated into knitted smart textiles.

1. Introduction

Smart textiles contain sensory or actuator elements which can react to and interact with the environment. Such elements can, e.g., be used to measure breathing frequency, ECG or pulse [1], skin temperature, sweating and other vital signs. They can illuminate clothing for safety or design purposes, e.g. by LEDs or optical fibers [2]. Reactions on temperature changes and other environmental conditions can also be performed by textile-integrated phase change materials or similar “intelligent” materials [3].

In many smart textiles, electronic components play an important role to achieve desired functionalities. These parts have to be connected to transport energy and data. Conductive paths in textiles can either be generated by common wires or by conductive yarns, with advantages and problems occurring in both cases. While wires tend to work hardening and breaking during washing and use, conductive yarns may also break or oxidize, depending on their composition.

3 To whom any correspondence should be addressed.
Especially the integration of conductive yarns into textiles has been examined in recent years. Several techniques, such as weaving, sewing and embroidery, were used [4,5]. Connection technologies between non-textile sensors and actuators and textile panels [6] or yarns [7] were investigated, too. These projects, however, dealt with non-elastic textiles as bases for conductive paths.

Since neither wires nor conductive yarns are really elastic—even so-called “elastic” conductive yarns can only be elongated by a few percent [8, 9]—, both solutions necessitate nonlinear integration in sensory underwear and other elastic clothing and textiles. It has been shown that sewing conductive yarns in undulating forms meets the demands of elastic underwear [10].

A simpler method, however, is to directly use conductive yarns or wires during knitting to produce an elastic fabric with integrated conductive paths. This approach was followed in a recent project, aiming at a comparison between wires of different materials and diameters. Additionally, one conductive yarn was included in the experiment. An overview of the samples under examination is given in the next section.

2. Experimental
Table 1 depicts the different wires and an additional conductive yarn which were used in the recent study.

| Material                      | Diameter  |
|-------------------------------|-----------|
| Cu (copper)                   | 0.23 mm   |
| CuAg7 (copper silver 7 %)     | 0.15 mm   |
| Ni (nickel)                   | 0.10 mm   |
| NiCr (nickel-chrome)          | 0.10 mm   |
| StSt (stainless steel) AISI 316 L | 0.05 mm |
| Shieldex (silver-plated nylon 66), prod. by Statex | 235/34 dtex 2-ply |

For knitting, a single-bed hand flat knitting machine SilverReed SK-280 with gauge E5.5 was used. The following structures were produced: single jersey (all materials); stitches and tucks alternating in course and wale direction (samples T), and stitches and floats alternating in course and wale direction (samples F) (NiCr only). All samples included 5 single courses of conductive material, separated by 8-10 courses of non-conductive yarn (PAN Nm 22/2).

The samples underwent the following tests: washing at 60 °C with heavy-duty detergent and concurrent spin-cycle of 800 min⁻¹; bursting tests using a TruBurst 611 (James H. Heal) with 22 mm bulging height for 10 cycles; and elongation tests using a tensile testing machine with 25 % maximum elongation for 10 cycles. In the latter test, the samples were elongated along the courses.

The samples were examined using the industrial X-ray system X-Cube 225 of GE Measurement & Control Solutions with a minifocus after knitting as well as after the aforementioned tests. The X-ray parameters are: 64 kV, 2.1 mA, focus diameter 0.4 mm, exposure time 100 ms, gain 1100, 16 iterations, and flash filter. In this way, the conductive courses can be depicted separately, without the overlaps by non-conductive yarns which would occur in an optical microscope and hide parts of the conductive materials.

3. Results
During knitting, the following experiences were made: The Cu wire needed to be unwound tangentially because the twist in the wire became too strong to guide it correctly through brake, thread guides and yarn carrier. It never broke but sometimes caused missed stitches.
CuAg7 was even harder to knit due to its high bending stiffness. During the 4x5 courses, it broke 3 times.
Ni and NiCr were easily unwound and knitted; they never broke.
Stainless steel had to be knitted slowly and tended to get in contact with the non-conductive yarn alongside. Due to its elastic behavior (opposite to Cu which tends to bending plastically), it was hard to keep away from the other yarn. It broke 5 times during the 4x5 courses.
Shieldex yarn, finally, behaves identical to each “usual” yarn and is knittable very well.
Samples of all materials and structures were examined using X-ray directly after knitting. Fig. 1 shows the results (only one representative conductive line per sample).

![Figure 1. X-ray images of all samples directly after knitting. Shadows can be attributed to the sample holder. Sample names are explained in Table 1 and the text below.](image)

Apparently the Cu wire is too thick to create stitches in the usual shape. Irregularities are visible in all knitted courses (here in the middle of the course, with bent stitches and decreased loop widths).
CuAg7 looks much more regular, with the stitches all bent in the same direction, as usual for typical yarns. 

Ni and NiCr show similar shapes, with the loop heads being more pronounced than in CuAg7, but some irregularities.

Knitting with stainless steel results in over-pronounced loop heads and strong buckles in the stitch shapes.

Shieldex produces common stitch shapes, as expected from a usual yarn.

Both additional knitted structures exhibit the expected loop shapes with not completely rounded stitch heads and some irregularities in the complete courses.

![X-ray images of all samples after washing. Sample names are explained in Table 1 and the text below.](image)

**Figure 2.** X-ray images of all samples after washing. Sample names are explained in Table 1 and the text below.

Fig. 2 shows the samples after washing. Cu and CuAg7 stitches do not change their shapes visibly. NiCr and especially Ni, however, show much more irregular structures after washing. The same
observation applies to the stainless steel stitches. Shieldex – as expected for a nylon yarn with only thin metallic coating – retains its regular structure. Regarding the additional knitted structures from NiCr, the T version looks more irregular than directly after knitting, while the F version shows only small deviations from the original shape.

In Fig. 3, X-ray images of the samples after repeated burst tests are depicted. Cu and CuAg7 again do not show significant deviations from their original shape. Ni and NiCr also show less deformation than after washing. The same finding holds for the other materials. Apparently, the regular tension in the repeated burst tests is less strenuous for the wires than the irregular stress during washing.

The results of repeated linear elongation by 25 % are depicted in Fig. 4. Similarly to the results of the aforementioned demands, Cu and CuAg7 are nearly unaltered in comparison to the original knitted structures. The nickel wire, however, has significantly changed its form. Opposite to the bursting test
in which an isotropic force is applied on the knitted fabric, in the tensile test only a force along the courses works on the textile. This leads to a significant difference between the shape of the loops before and after elongation.

NiCr and stainless steel wires remain apparently unaltered. In the same way, NiCr in T and F version stay nearly unchanged.

Another important parameter of conductive materials, besides their mechanical properties, is their conductivity. Thus, the resistances of all conductive materials under examination were measured directly after knitting as well as after washing, bursting and elongation tests, using a multimeter with clamps. It should be mentioned that in this way, the overall resistance is composed of the contact resistance between multimeter clamps and knitted wire / yarn, and the linear resistance in the conductive material.
In all wires, the overall resistance stayed unaltered after washing, bursting and elongation tests. A significant difference, however, was found for Shieldex yarn after washing, where the resistance increased by approximately a factor of 2-2.5. Since microscopic inspection of the Shieldex yarn after washing did not reveal a possible reason for this finding, this issue will be investigated further in the near future.

Table 2. Rating of the materials under investigation during knitting and subsequent tests, with positive (+), negative (-) and neutral (0) rating.

| Material  | Knitting | Washing | Bursting | Elongation |
|-----------|----------|---------|----------|------------|
| Cu        | -        | +       | +        | +          |
| CuAg7     | -        | +       | +        | +          |
| Ni        | 0        | -       | 0        | -          |
| NiCr      | 0        | -       | 0        | 0          |
| Stainless steel | -       | -       | 0        | 0          |
| Shieldex  | +        | -       | +        | +          |

To conclude, Shieldex yarn is ideally suited for applications which do not need to be washed. In other applications, wires may be good alternatives, depending on the requirements and possibilities during knitting as well as the mechanical demands during usage. Especially Cu and CuAg7 show good resistance against washing, bursting and elongation. Other materials and wire diameters may be more suitable for other applications.

Nevertheless it must be stated that none of the materials under examination can be attributed as perfect for all applications. This finding shows the necessity of further investigations, taking into account other conductive yarns, stranded wires etc.

4. Conclusion
Conductive yarns or wires, used for energy or data transmission in smart textiles, still suffer from some issues, compared to usual textile materials. They may be hard to knit and change their mechanical and electrical properties during washing or mechanical stress.

In a recent project, we have shown the possibilities of investigating conductive yarns and wires integrated in textile fabrics by X-ray examinations. In this way, the advantages and disadvantages of different wires and a conductive yarn could be shown.

In future projects, different wires and conductive yarns will be examined further, using the X-ray technology to enable visual inspection of the complete conductive materials’ shapes without impairment by the neighboring non-conductive courses.

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