Coating of electroconductive sewing threads to preserve the functionality of the textile resistive strain sensors

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Sewing is a straightforward technique used to produce textile strain sensors integrated into tight-fitted garments to monitor body movement. In comparison with other common production techniques such as printing, coating, embroidery, weaving or knitting, sewing has some advantages. For instance, stitched strain sensors may be produced by conventional sewing machines during confectioning of the garment which happens later in the production stage and therefore they don't require any additional equipment. They can be also applied on the desired place on the garment, saving therefore electroconductive (EC) yarns and avoiding problems like cutting of the electrical circuit during garment pattern making. Moreover, these strain sensors may be potentially easier connected to the read out and processing electronic components and may also be easily disassembled and disposed at the end of life of the product if fabric recycling is required.

Resistive strain sensors can be obtained by stitching EC sewing threads with high electrical resistance on a textile substrate, using different type of stitches. EC sewing threads such as HC12® and HC40® (Madeira), Silvertech® and Silvertech+® (Amann), Shieldex® (Statex), Elinox® (Soieries Elite), Magellan® (Coats), etc. are commercially available in various range of counts and electrical resistance. Commonly they consist either of a (silver) plated textile multifilament i.e. polyamide (PA) or polyester (PES) or of a metal wire (i.e. stainless steel, copper) wrapped with textile yarns of different origins depending on the application. Figure 1 shows examples of two type of stitches realized with various type of EC threads.

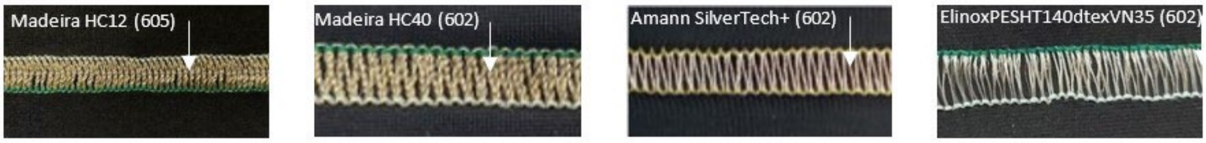


Figure 1 Examples of stitches 605 and 602 (ISO 4915:1981) using various EC-threads as cover thread (close-up stitch front)

Important parameters of the stitched sensor are its accuracy (linearity R^2), working range WR (%), the response time (s), hysteresis H (dynamic durability) and gauge factor GF (sensitivity). An example of the behaviour of such textile resistive strain sensor is illustrated in Figure 2, which shows the variation of electrical resistance (ohm) with the strain (%) for an uncoated Madeira HC40 sensor, stitch type 602, after 10 cycles of loading-unloading. In this case, the sensor (with Madeira HC40 uncoated thread) has a WR between 5-15% (linear part of the curve) and has a high accuracy R^2= 0.87 (the slope of the curve over the WR). Typically, such a sensor is working properly only within WR, beyond which it also displays an (unwanted) hysteresis between a loading and unloading cycle, as illustrated in Figure 2 at 30% and 40 % strain. The sensitivity of the sensor is given by its GF (GF=(ΔR/R0)/strain), which is the magnitude of the resistance change over applied strain.

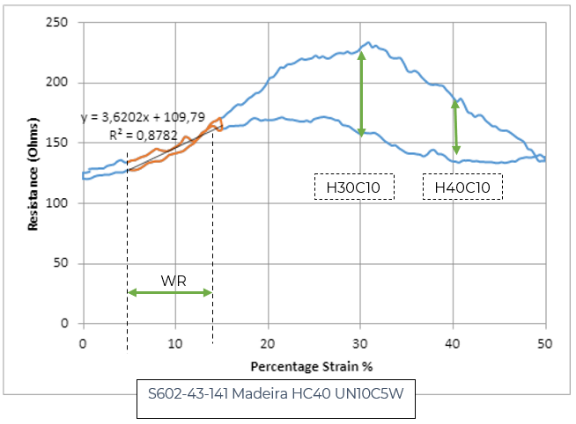


Figure 2 Example of the strain sensor parameters working range (WR), linearity R^2, hysteresis H30 and HC40 at 30% and 40% strain for the Madeira HC 40 sensor with uncoated threads

These parameters tend to change with washing which is a basic practice for the maintenance of garments. Sensor durability upon multiple stretch cycles (SC) and garment washing cycles (WC) must be preserved, regardless of the EC sewing thread type used. However, for commonly used PA 6.6 silver-plated sewing threads (i.e. MADEIRA HC40® and HC12®) only low temperature (30°C), mild washing is recommended by the manufacturer to avoid loss of functionality upon washing. Moreover, some other sewing threads (i.e. Elinox®) may exhibit low sewability due to limited interlacing between the rather different components (i.e. PES multifilament and stainless-steel wires VN35) twisted together in various architectures.

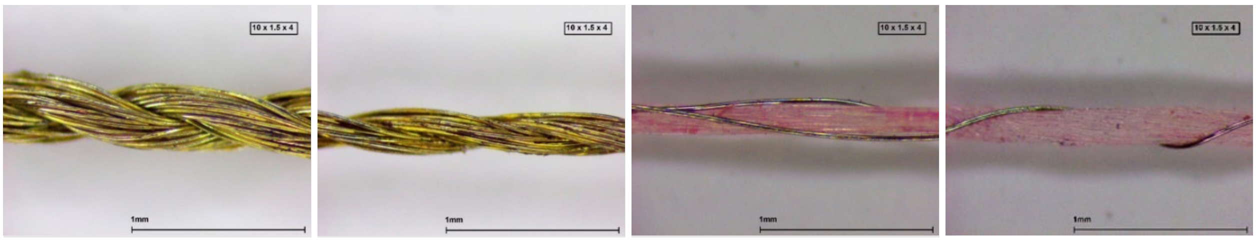
To address these drawbacks and preserve the performance of the strain sensor, a water-based PES-PU coating was applied on different types of EC-threads. The EC-threads (Table 1) were coated with ICO-THANE ST 10® (95% wt) and LAGO® (5% wt) at a dilution rate of 1:4, using a pilot dip coating and drying unit Mathis (Figure 3) at a speed at 1 m/min and drying temperature 120°C. ICO-THANE ST10® is a PU-based aqueous dispersion compound developed for sewing threads and LAGO45® is a PU-based product that enhances adhesion between the coating and the yarn substrate. Both components are commercially available.

Table 1 Characteristics of the EC-sewing threads

EC-yarn	**Tex**	**Linear resistance of uncoated EC- treads (Ω/m)**	**Coating pick-up (%)**	**Linear resistance of coated EC- treads (Ω/m)**
Madeira HC12	62	49±1	4.03	51±2
Madeira HC40	30	151±4	4.92	238±9
Elinox PES140dtex2VN35	30	101±1	6.6	437±32
Elinox PES280dtexVN35PES20dtex	40	865±7	4.94	978±8

The coating pick-up was between 4 and 6.6 % depending on the EC-thread, as it can be seen in Table 1, which also shows an increase of the electrical linear resistance of the EC-threads due to the coating. Some examples of coated threads are illustrated in Figure 4.

Figure 3 Pilot line: dip coating and drying unit (Mathis)



(a) (b) (c) (d)

Figure 4 Examples of coated threads: (a) Madeira HC12, (b) Madeira HC40, (c) Elinox PESHTdtex1402VN35 and (d) Elinox PES280dtexVN35PES20dtex

Resistive strain sensors were prepared by stitching the coated threads (Figure 4) on an elastic polyamide knitted fabric (80/20 PA/EL, 219±1,7 g/m^2, thickness 0,6 mm) using stitch type 602. The strain sensors, were subjected to several mechanical loading and unloading cycles within a stretch range of 0-50%, using a tensile tester Lloyd with a gauge length of 100 mm at constant speed of 200 mm/min. The tensile tester was equipped with a data acquisition system DAQ (Figure 5) to allow automatic resistance-strain registration. The effect of the coating on the sewability of all coated threads was observed. Performance parameters of the sensors were calculated after 10 stretch cycles (SC) and in the case of the Madeira sensors also after 10 SC followed by 5 washing cycles (WC) and 20 SC/ 10 WC.

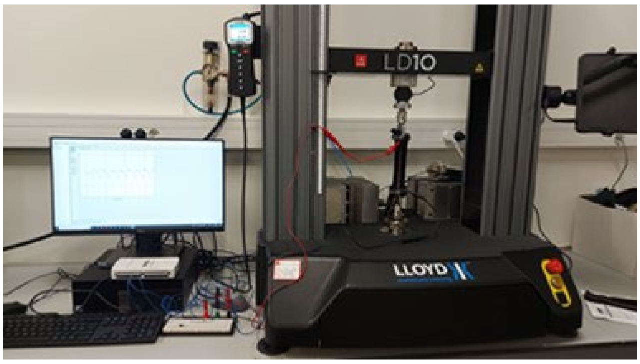
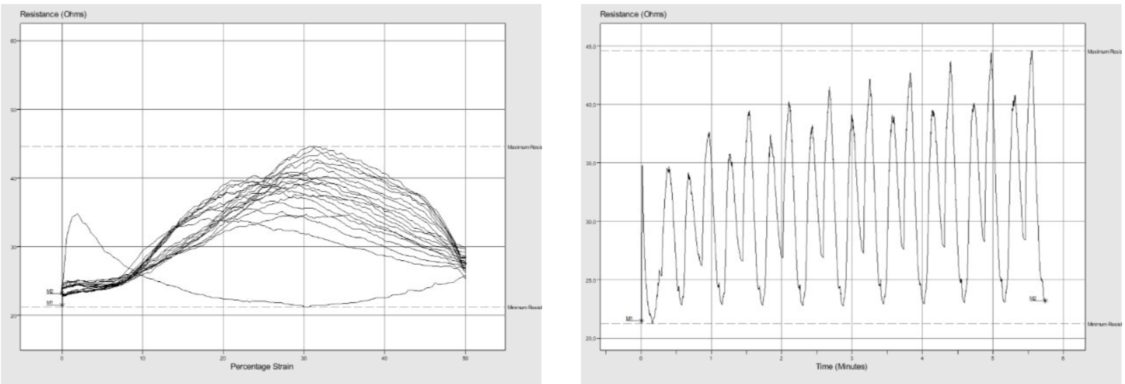


Figure 5 Test set-up: tensile tester and DAQ

All Madeira sensors showed a good linearity in the working range of 5-15% stretch, the coated sensors in particular (R^2=0.8-0.9). These sensors became stable after the second stretch cycle, so the response time was estimated at about 60 s. The results suggest that the sensors with coated threads Madeira HC12 and HC40 have a better resilience than the control sensors with uncoated threads. The coating positively affected the sensor's hysteresis, which decreased after coating and was not much affected by the number of WC or SC applied. An example of the behaviour of a coated Madeira HC12 threads sensor ca be seen in Figure 6.



(a) (b)

Figure 6 Example of coated MadeiraHC12 sensor after 5 WC: (a) resistance vs. strain and (b) resistance vs time (10 SC)

The coating uptake between 4.3-6.6 % did not significantly improve the sewability of the Elinox threads. Moreover, these two Elinox sensors displayed only small changes of the electrical resistance upon the large stretch range of 0-50%, therefore they would be recommended as conductive tracks rather than resistive sensors.

The results of this study suggest the possibility to preserve sensor functionality by applying coatings. However, the consistency of the results should be demonstrated after a larger number of load-unload cycles (preferably within the found working range of up to 20% stretch) and washing cycles. The process can be further fine-tuned aiming at optimisation of the process parameters and compounds ratio. Potential additional beneficial effects of the coating such as less friction between the needle and the coated yarn could be also investigated by using IR-thermography over an appropriately long period of (sewing) time.

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