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Electro-mechanical endurance tests on smart fabrics under controlled axial and friction forces

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Abstract

The design, building and validation of machine for endurance tests on fabrics are described in this paper. The system is addressed to the reliability testing of smart fabrics with electrical conductivity. The development of e-textiles, in fact, requires innovative test benches for the evaluation of performances decay with load cycles accumulation; the proposed system is able to monitor the electro-mechanical parameters of fabric sample in the same time in order to support industrial development and predict failures on final applications.

Keywords: electro-mechanical reliability; lifetime; experimental mechanics; wearable sensing

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1. Introduction

Smart fabrics consist in textiles featuring woven electronics and interconnections. The mechanical properties of smart fabrics, in terms of flexibility and strength allow creating many applications of wearable electronics that cannot be realised with other existing electronic manufacturing processes.

The rapid evolution of wearable electronic drives the grown interest in smart textiles Stoppa et al. (2014) and many applications have already been developed, in different fields. As some examples, in medical and biomedical many wearable devices have been developed: electrocardiogram (ECG) electrodes Cho et at. (2011) , electromyography (EMG) Linz et al. (2007) , and electroencephalography (EEG) Löfhede et al. (2010), temperature measurement

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Sibinski et al. (2010) . Other applications consist in shape-sensitive fabrics combined with EMG sensing used to perform muscle fitness Meyer et al. (2006), functionality, or assistive technology by radio frequency (RF) Black (2007).

Sensors integrated into fabrics have been used to detect specific environmental or biomedical parameters Coyle et al. (2010), and fabrics containing luminescent elements have been used for biophotonic sensing Omenetto et al. (2013). In electronics and telecommunication smart fabrics find application as electromagnetic shields Aniołczyk et al. (2004) , but also as distributed body-worn communication system Ouyang et al. (2008) and wearable antennas Wang et al. (2013), Salonen et al. (2003) . Another interesting application consists in human interface elements De Pasquale (2015), De Pasquale et al. (2016).

Dedicated fabrics have been developer for the energy generation and storage Vatansever et al. (2011), using piezoelectric Edmison et al. (2002), De Pasquale et al (2013), De Pasquale (2016) or photovoltaic devices Bedeloglu et al. (2009). Integrated micro electro mechanical systems (MEMS) De Pasquale et al (2009a), Ballestra et al. (2010), De Pasquale et al. (2009b), De Pasquale (2009) are also finding application in this field.

Despite the fast development of smart textiles manufacturing, the characterization procedures and design standards to certificate the electro-mechanical reliability of final products have not been developed and established and exhaustive test procedures and predictive models able to determine the combined electrical and mechanical reliability of fabrics are still not available.

Although many standard tests are available for traditional fabrics, they are not fully relevant for smart textiles where the electro-mechanical coupling is fundamental.

Actually, smart fabrics when worn are subjected to variable mechanical loads and wear that may cause failure in electronic connections, therefore the electrical continuity must be guaranteed during the whole life of the smart clot. Only few works concerning mechanical characterisation may be found in the literature, consisting in washing tests of ECG electrodes Hoffmann et al. (2007) and relaxation tests of conductive knitted fabrics for breathing sensors Qureshi et al. (2011), Atalay et al. (2013).

Therefore, comprehensive procedures and test methods are required to satisfy the design requirements of advanced applications involving smart fabrics.

The aim pf this work is to propose a test procedures where the sources of failure can be controlled and combined together to show cross-talk effects such as between load and wear cyclic loads and current flow, etc.

In particular in this work a novel test rig and the related experimental procedure to validate performances and reliability of smart fabrics under fully controllable conditions is presented.

The testing machine has been designed and a prototype manufactured. The test rig allows accelerated life tests with controlled conditions by coupling the effects of cyclic loadings equivalent to operative conditions, wear effect and electricity flow.

Nomenclature

D_c	duty cycle
f	friction coefficient
F	tensile force
F_0	axial preload
F_f	friction force
F_{max}	maximum force magnitude
h_0	clamp height
K	springs stiffness
L	sample length
L_0	clamps distance
$v1$	rotation speed
Δl	springs elongation
θ_a	active phase

2. Test rig concept and design

The testing device and the related testing procedure presented in this work have been developed to investigate the effects of multiple sources of failures such as wear and tensile loads on the performance of smart fabrics.

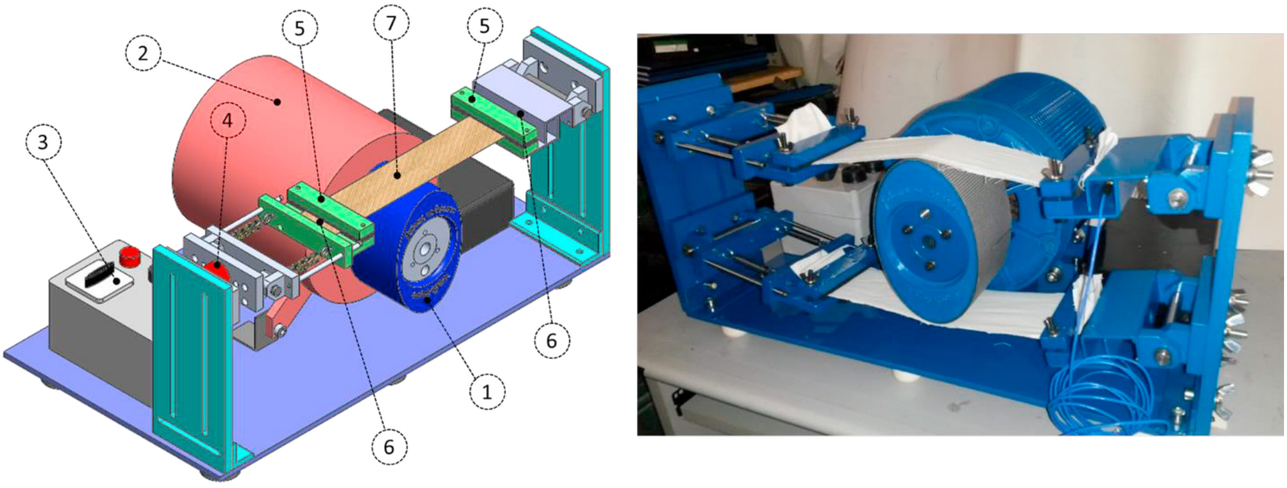
The proposed test rig allows also to investigate the electro-mechanical coupling of smart fabrics, by monitoring the electrical performances decay induced by fabric damage. Moreover, testing apparatus can perform accelerated tests to estimate the fabrics lifetime by means of predictive models.

Fig. 1 shows the schematic and a picture of the developed test rig within its main parts. The smart fabric sample to be tested is mounted on the test rig by two lateral clamps (5), then cyclic tensile and friction loads are applied to the sample by means of a rotating elliptical pulley (1). The loads consist in mean and alternate components, which are both adjustable. Coupled loads can be generated along weft and warp according to the sample orientation.

Tear resistance and seam strength in combination with friction-induced wear can be evaluated by using pre-cut samples.

The elliptical pulley is put in rotation by a 400W power single-phase induction motor. The pulley can be coated with different materials in order to change the coefficient of friction and test the sample with different surfaces patterns and materials. Moreover, by using dedicated pulley coatings, it is possible to perform abrasion tests and pilling tests.

The electric properties of smart fabrics are monitored in real time by means of an electronic detection system connected to the sample by their electric connections (6), allowing to monitor the resistivity increase of wires embedded into the fabric during the progressive textile damaging induced by mechanical loads.



(a) (b)

Fig. 1. Functional schematics of the endurance testing system including: 1) elliptical actuator; 2) electric motor; 3) control panel; 4) load cell; 5) sample clamps; 6) electric connections; 7) fabric sample (a) and endurance testing system during experimental characterization of samples (in double samples configuration) (b).

The sample clamps (5) can be positioned at variable heights acting on adjustment screws. The testing machine allows two samples to be mounted and tested at the same time. Initial preload can be adjusted acting on the springs that connect one clamp to the frame of the machine. The other clamp is connected to the frame trough a load cell (Burster series 8435 +/-1kN) (4) that provides the measurement of the instantaneous load applied to the sample. The motor speed and rotation direction (clockwise or counterclockwise) can be modified thanks to a dedicated electronic system. In particular, two speeds are available: 480 or 2900 rpm.

The electrical parameters associated to the smart fabric (e.g. the electrical resistance of embedded conductive wires) are measured by the ADC (analog-to-digital converter) at 50 Hz sampling rate (National Instruments USB-6001).

Smart fabrics have usually anisotropic behavior therefore the proposed test bench allows measuring the electric output in the same direction of the mechanical load or, alternatively, in the orthogonal direction just by modifying the sample clamping position. In addition, if the measurement is repeated in two different orientations it is possible to obtain the 3-1 3-3 coupling coefficients of the orthotropic conductive fabric.

The variable load applied on the textile sample is basically composed on a tensile force F (applied along the main direction of the sample) and a friction force F_f, that depends on the tensile force and the coefficient of friction De Pasquale et al. (2017) .

Thanks to the design of the test rig it is possible to reproduce on the sample a loading pattern as represented in Fig. 2 De Pasquale et al. (2017).

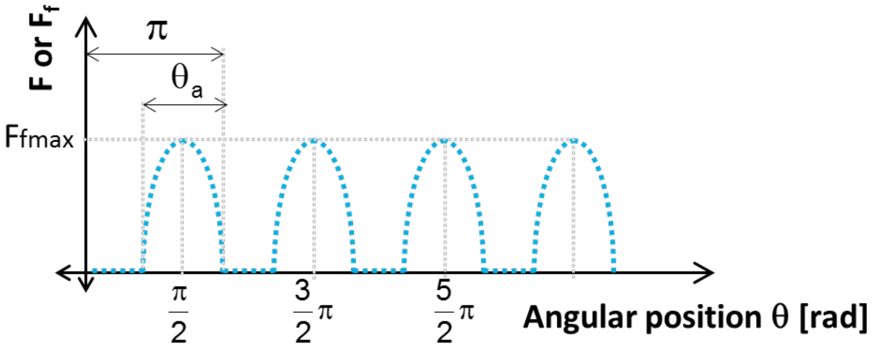


Fig. 2. Qualitative profile of the friction force on the sample.

In particular, the load shape is characterised by the loading duty cycle (D_c), defined as the ratio between the active phase θ_a (in radians) and the angle π:

$$D_c = \frac{\theta_a}{\pi} \tag{1}$$

The two extreme conditions are when the duty cycle is $D_c = 1$ (sample is always in contact to the actuator), and $D_c = 0$ (sample is always unloaded), all the intermediate loading conditions can be adjusted by modifying the sample position and preload.

Thanks to its peculiarities, this endurance testing system is able to perform accelerated tests, under the effects of variable loads, reproducing the real working conditions of smart (and traditional) fabrics, providing realistic estimation of the lifetime.

3. Test bench validation: endurance tests of smart fabrics

The samples used for electro-mechanical characterization, reported in Fig. 3 (Technofabric (2017)), are made with nylon and copper conductive fibres with 90μm diameter. The load applied to each sample is varied among test sessions (as well as the number of cycles) and controlled in amplitude.

Two working speeds are provided to the test rig: 16 and 96 cycles/s. The preload is applied to the samples through the calibrated spring with stiffness 6.4 N/mm, providing initial load values F_0 = 13.5, 28.6 and 80.2 N respectively.

The friction force applied to the sample is controlled by means of the friction coefficient of the rotating pulley, which value is set to 0.36 (from Anton Paar tribometer measurement) for current tests. Table 1 reports setup parameters of the tests.

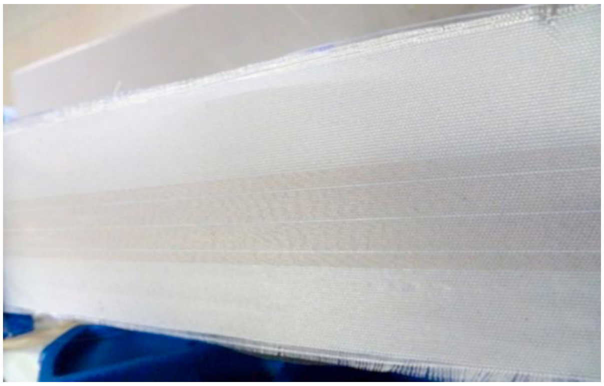


Fig. 3. Sample detail with conductive copper fibers.

Table 1. Test bench parameters and experimental setup.

Parameter	Value	Unit
E-textile specimen length	200	mm
Preload springs stiffness coefficient	6.4	N/mm
Preload springs stiffness elongation	2.23	mm
Axial preload	13.5 - 28.6 - 80.2	N
Friction coefficient	0.36	
Rotation speed	480	rpm

The results of the endurance tests for two samples are reported in Fig. 4. The graph reports the increase of electrical resistance due to progressive damage of conductive fibers.

The rotating pulley produced controlled abrasion of fabric sample generated by the friction force against the pulley coating with known friction coefficient. The steps present in the graph represent the failure of single conductive fibers, which produce increasing of global fabric sample resistance.

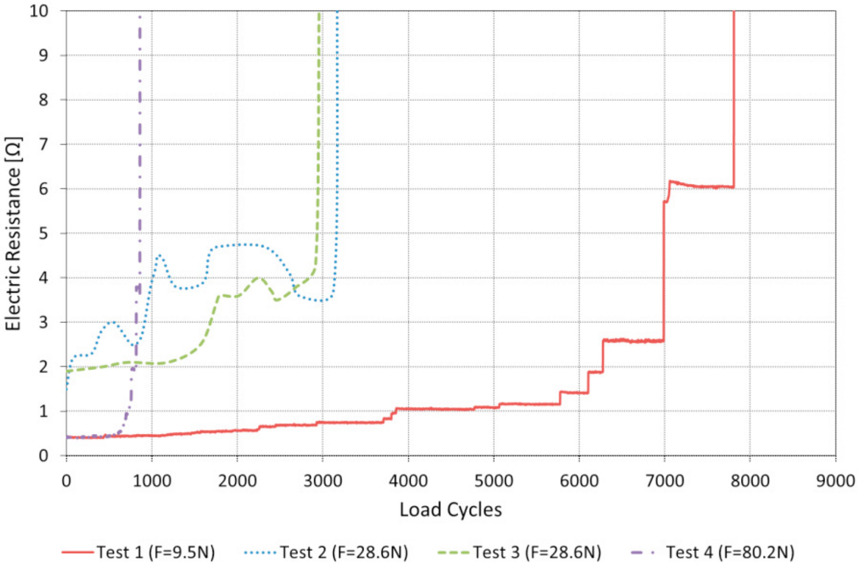


Fig. 4. Global electrical resistance variation on different fabric samples with different loads applied.

The fabric embeds the electric conductive fibers along the warp direction; the fibers oriented in the weft direction are subjected to sliding due to the interaction with rotating pulley surface. The result is cumulative degradation of fibers and strip of copper conductive elements.

After some time, the first metal fibers start the internal damaging process, which leads finally to their rupture. The ultimate conductivity effect of the sample is lost when the last electric fibers collapse. In Fig. 5 the final aspect of samples after endurance testing is shown.

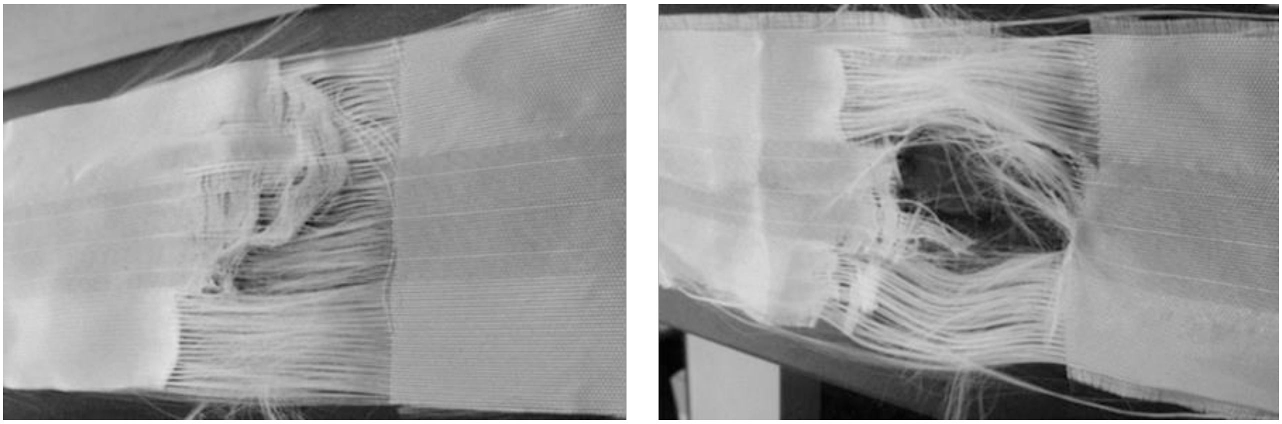


Fig. 5. Visual aspect of two samples after endurance test.

4. Conclusions

The paper presented the design, building and validation of endurance test bench for e-textiles. The test bench innovation consists in the possibility to test sample by reproducing the real axial and friction forces acting in working environment and by measuring the electro-mechanical decay at the same time during cycle accumulation.

In fact, the test bench provides cyclic loading to the sample instead of continuous friction, differently from the devices normally used for fabric testing. This peculiarity is motivated by the needing of reproducing effective operative conditions of e-textiles (contact with other fabrics, with human body or rigid surfaces).

The performances decay of e-textile samples can be converted to the effective lifetime of final products by means of some relevant parameters. For instance, the operative frequency and forces scaling or friction coefficients modulation can be used for lifetime prediction.

The tests reported in this study reveals typical damage process of synthetic fabrics subjected to abrasion and mechanical wear. The sequential fibers collapse has been observed and quantified in terms of electrical conductivity lost. The complete loss of conductivity is reached at cycles number variable depending to the external forces applied.

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