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Electrically conductive inks: the role of graphitic materials

A. Sironi,* P. Milana,§ G. Rocco,* C. Fontanesi,* F. Margani,§ M. Galimberti§

*Eptatech SRL, via De Gasperi 1 - 22070 Luisago (CO)

§Politecnico di Milano, Dip. Chimica, Materiali, Ingegneria Chimica, via Mancinelli 7 - 20131 Milano

Introduction

Electrically conductive inks are the foundations of **printed electronics** as they allow to print circuits on different surfaces. One of the most appealing applications is the embedding of these circuits in wearable items, but they must not lose their functional performances undergoing stretches and bends due to body movements.

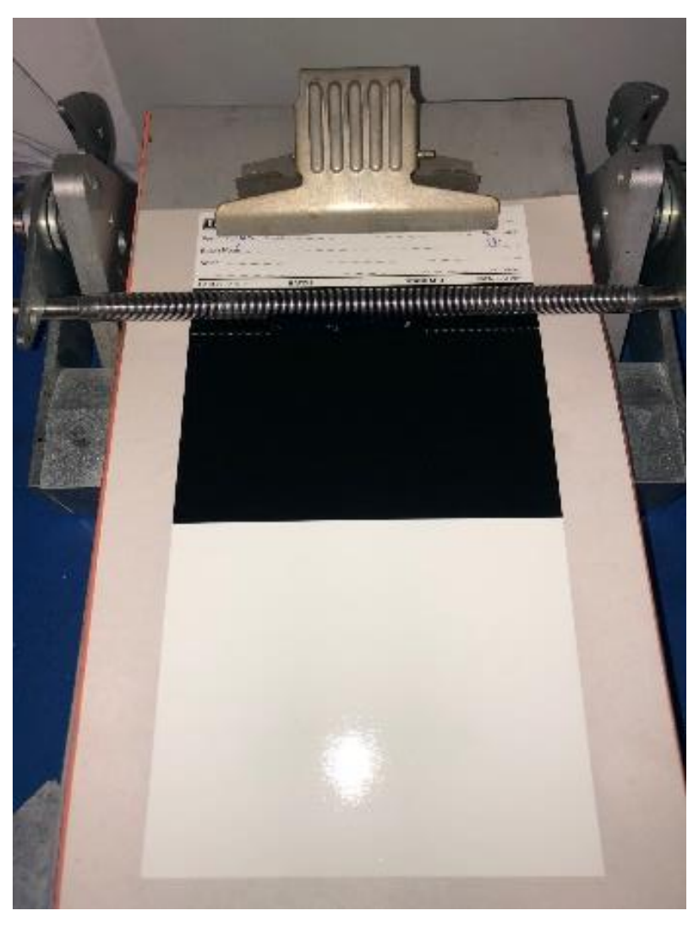
To fulfill this objective, conductive fillers, usually **silver materials** and **carbon allotropes**, are dispersed in an elastic polymeric matrix; as to carbon allotropes, some dispersion problems arise since no surface treatment able to enhance compatibility with organic polymers is generally present in commercially available materials.

Relying on a known functionalization technology [1], preliminary lab tests and industrial-grade ink formulation experience, we have managed to produce **screen-printable, carbon black-based, water-based inks** and to evaluate the role of the addition of graphitic materials in improving their conductivity.

Preliminary lab tests

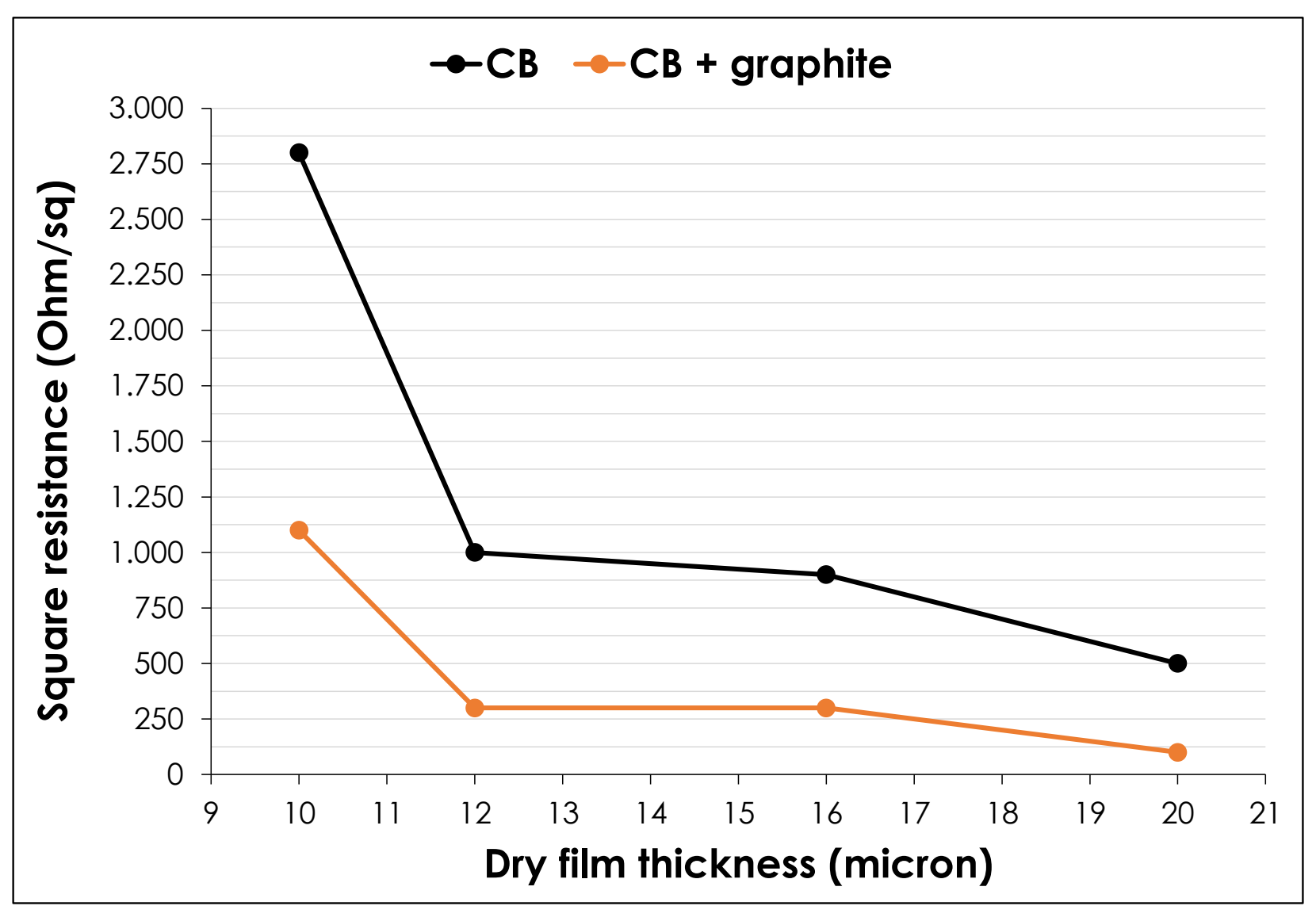
A structured conductive carbon black and a graphite have been chosen as the fillers for a non-elastic resin commonly used in the coating industry. Carbon black was chemically functionalized before use. Two different water-based formulations (with the **same overall amount of conductive filler**) were stirred at room temperature for 24h, then applied on Leneta cards at different thicknesses by means of a bar-coater. After drying in air, square resistances were measured with a multimeter. As it can be seen, the **substitution of 1/3 of CB content with graphite** allows an important decrease of the resistance, especially at a low coating thickness.

Ink Formulation



Deposition with bar-coater

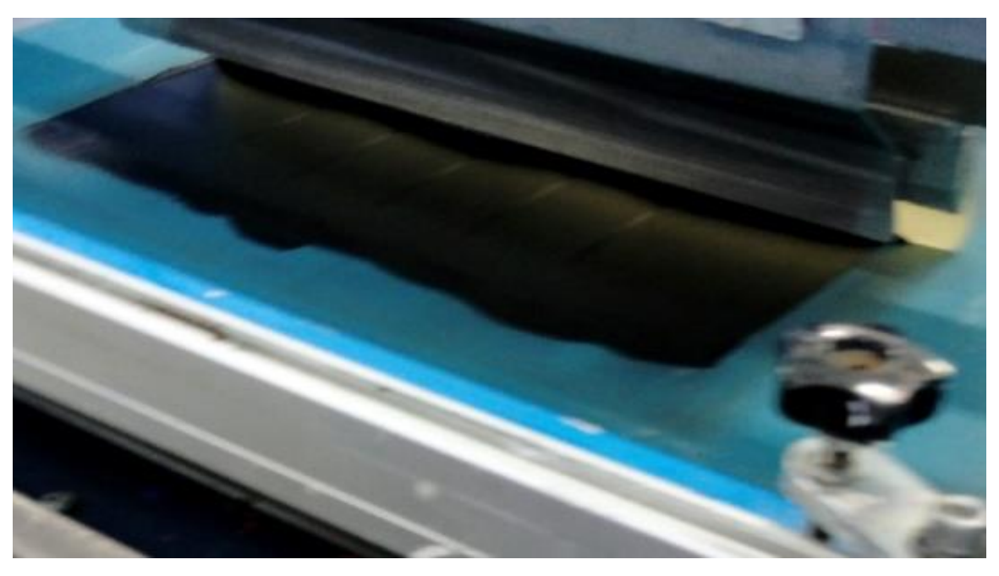
Deposited Conductive Layer



Industrial-grade inks

Two screen-printable water-based inks suitable for stretchable electronics applications have been produced by mechanically dispersing the **same amount of carbon filler** (CB alone or CB and graphite, 2:1 w/w) into an elastic polymer matrix. Both inks were homogeneous, foam-less, with a medium-high viscosity and thixotropic. The chemical functionalization of CB proved to be effective in helping its dispersion into the resin.

Ink Formulation



Screen-Printing Process

Printed Conductive Traces

Well defined traces have been **screen-printed** on a polyester sheet and the square resistance was determined with a multimeter.

Ink	CB	CB + graphite
Static square resistance	272.95 Ohm/sq	82.93 Ohm/sq

Then, samples to be tested under stretch were obtained by transferring (by means of a hot press) sets of printed overlaid conductive and insulating inks on fabric, following the so-called **transfer printing technique**, common in the textile industry.

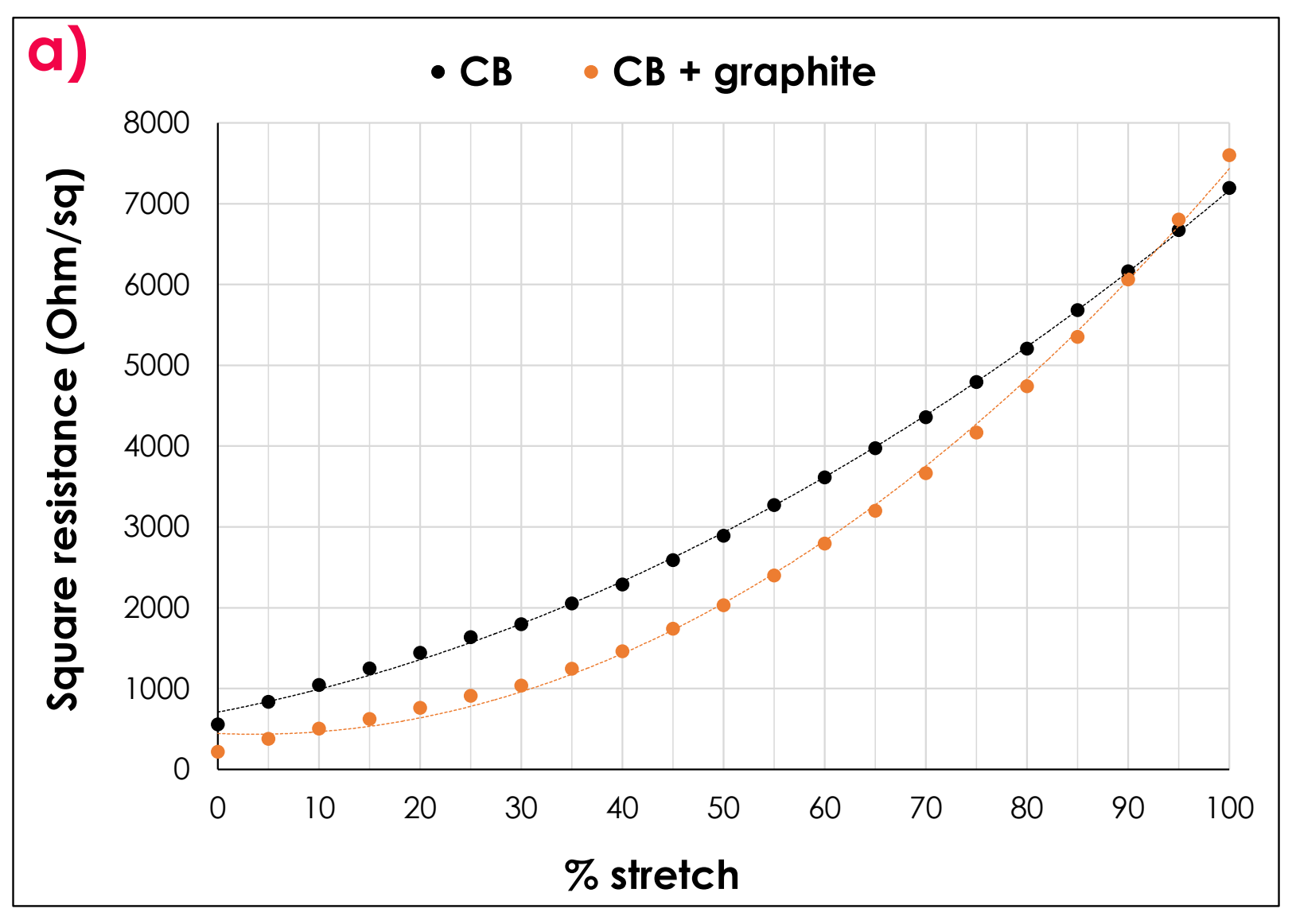
Electrical performances under stretch

Progressive elongation from the 0% stretch position to 100% stretch

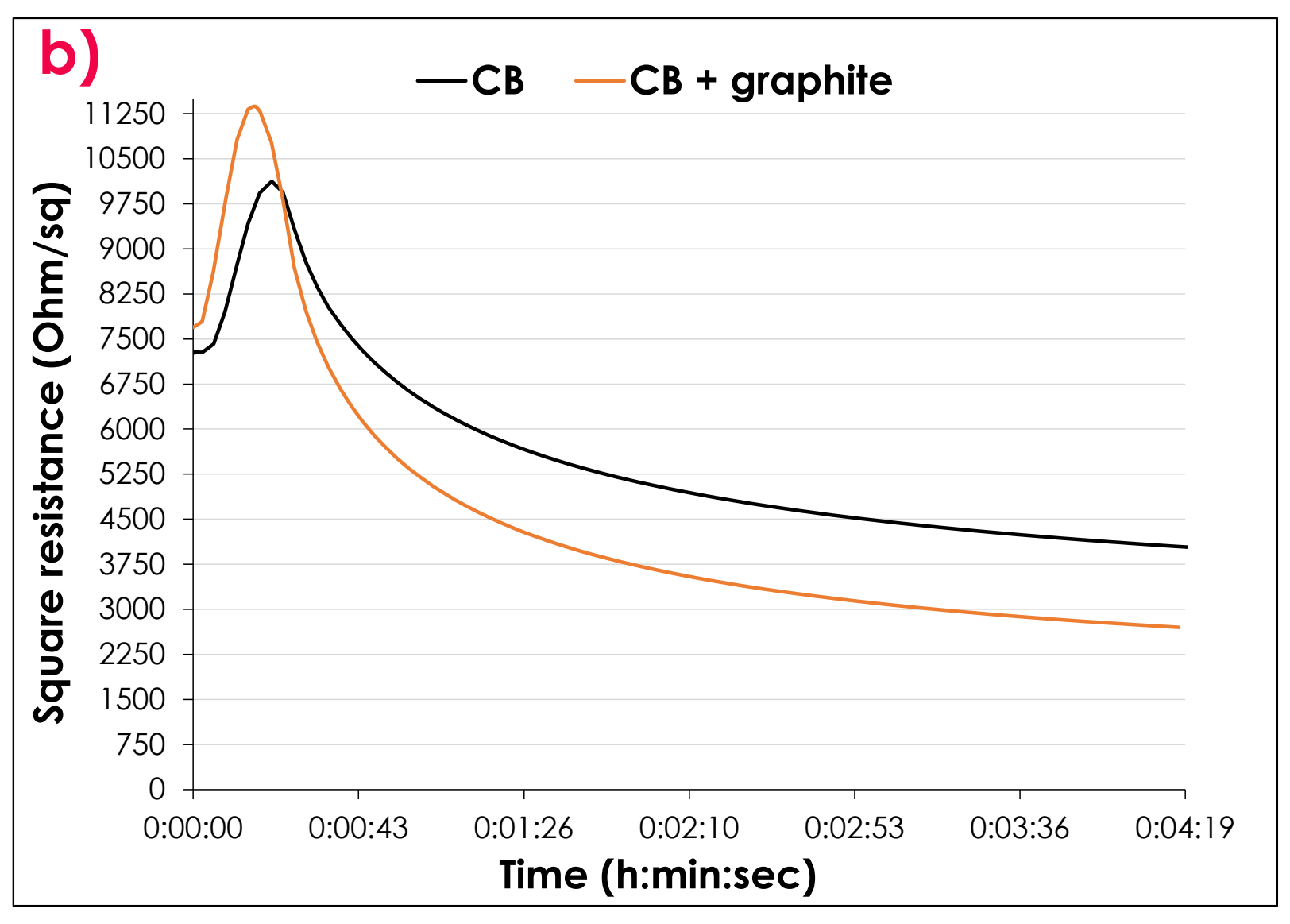
a) The delta between the two trends grows until 55% stretch when it starts to decrease and then eventually becomes negative at 95% stretch. It has been previously pointed out [2] that **CB aggregates and graphite platelets** are able to act **synergistically** and to **build a network** that lowers the percolation threshold. It is very likely that above 55% stretch this network starts to fail, with graphite platelets not effectively connecting CB aggregates anymore

b) An evidence of this mechanism may be the trends of square resistance when the samples are returned to 0% stretch position: the curve of CB + graphite ink is steeper than the one of CB ink since the connections by graphite bridges are gradually restored. However in both cases the final square resistance value is higher than the original one due to the strong deformation given.

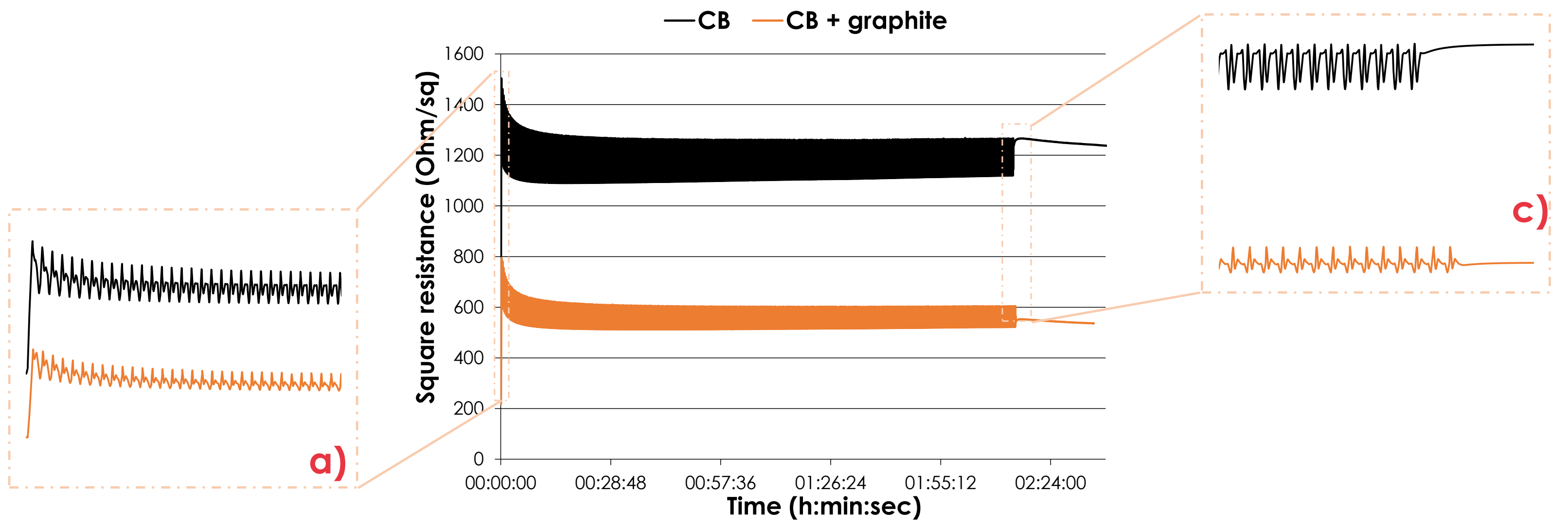
a)



b)



500 cyclic elongations (0% stretch position⇔ 20% stretch)



Three features are noteworthy:

a) the high peak corresponding to the very first elongation, due to the breaking of the static situation created by the printing, the transferring and the curing processes

b) the **very regular trend** the whole test duration long. An explanation may be the rearrangement of the percolation pathways that remains substantially unaltered for not so wide stretches, as pointed out in a previous paper [3]

c) the trend of square resistance at the end of the test.

The CB + graphite ink shows a lower initial peak and a less wide delta between minima and maxima with respect to the CB ink. Moreover, its square resistance stabilizes on a medium value when the elongations stop, while the one of CB ink initially tends to remain on the maximum value before decaying. All these favorable characteristics may be ascribed again to the extra connection between carbon black aggregates given by graphite platelets.

[1] a) M. Galimberti, V. Barbera, S. Guerra, L. Conzatti, C. Castiglioni, L. Brambilla, A. Serafini - *RSC Adv.*, **2015**, *5*, 81142-81152; b) M. Galimberti, V. Barbera, S. Guerra, A. Bernardi - *Rubber Chem. Technol.*, **2017**, *90*, 285-307
[2] a) M. Galimberti, V. Kumar, M. Coombs, V. Cipolletti, S. Agnelli, S. Pandini, L. Conzatti - *Rubber Chem. Technol.*, **2014**, *87*, 197–218; b) L. Valentini, S. Bittolo Bon, M. A. Lopez-Manchado, R. Verdejo, L. Pappalardo, A. Bolognini, A. Alvino, S. Borsini, A. Berardo, N. M. Pugno – *Comp. Sci. Technol.*, **2016**, *128*, 123-130; c) J. Song, W. Yang, X. Liu, W. Zhang, Y. Zhang - *Iran Polym. J.*, **2016**, *25*, 111–118
[3] L. R. Pahalagedara, I. W. Siriwardane, N. D. Tissera, R. N. Wijesena, K. M. N. de Silva - *RSC Adv.*, **2017**, *7*, 19174–19180