



Dynamic charge transfer between polyester and conductive fibres by Kelvin probe force microscopy

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ABSTRACT

Charge transfer processes between polyester and conductive fibre surfaces is studied using Kelvin probe force microscopy (KPFM). Three model systems are considered: a single isolated insulating polyester fibre, two conductive stainless steel fibres in galvanic or non-galvanic contact and an insulating polyester fibre in galvanic contact with a conductive stainless steel fibre. For first and third configurations, a two-stage process with two different time constants is observed corresponding to two mechanisms responsible for the charge transfer. For the second configuration, a single-stage process is observed. The presence of the conductive fibre facilitates the charge transfer on the insulating fibre.

1. Introduction

The demand for antistatic textiles has been growing up in the recent years due to the large number of potential applications [1–3]. In anti-static fabrics, the most widely used method to dissipate electrical charges consists in dispersing conductive fibres inside the highly resistive base fabrics. The crucial point is that the accumulated charges should be safely and quickly dissipated. Many efforts have thus been done to understand the charge and/or discharge mechanisms in order to better control the static electricity [4–9]. Especially, a previous study performed at the mesoscopic level on antistatic felts showed that the electrical resistance of the felts varies linearly with the geometrical parameter (length/section) [10]. In this study, a specially designed prototype also allowed the measurement of the surface potential distribution on a millimetre scale. The potential distribution was found to exhibit a complex non linear behaviour, including possibly non linearity and hysteresis effects. However, it was difficult to determine the exact configuration of the fibres in these felts. The objective of the present study is thus to measure the surface potential distribution on single isolated fibres or between two fibres in galvanic or non-galvanic contact in order to confirm the non linearity and hysteresis effects at the microscopic scale.

Generally, charges deposited on the surface of materials may be neutralized along different mechanisms that lead to a decay of their density. Measurements of the surface potential variation may thus help

to understand the charge transfer and/or discharge mechanisms [11–17]. In most conventional methods, a surface potential decay experiment involves the charging of the surface to a certain voltage using various charging methods, such as contact charging (with or without friction) [18–22], injection with an electron beam [23–25] or corona charging [11,14,17,26], etc. The time dependence of the surface potential due to the charge deposition and to discharge is then analysed. The charging mechanisms at play largely depend on the technique used for charging the surface and on the source of charge carriers.

Electrons can move “freely” in conducting materials. A charge deposited on a conductive surface will thus spread across the entire surface until an electrostatic force equilibrium is reached. On the contrary, electrons in insulating materials cannot move freely from atom to atom or molecule to molecule. Subsequently charge is seldom distributed evenly across the surface of an insulator. The charge transfer process on insulating surfaces is thus complicated and still not well-defined. In general, two main types of microscopic decay mechanisms are presented in literature.

First, charge dissipation can be done due to the so-called “external decay” mechanism that occurs via surface conduction and/or collisions with molecules in the surrounding atmosphere [26]. On a surface with constant surface conductivity, the first step of the charge decay is strongly influenced by the initial distribution of charges. Then, at longer times, the charge dissipation follows an exponential decay. A new idea is that charge dissipation is associated to adsorption and

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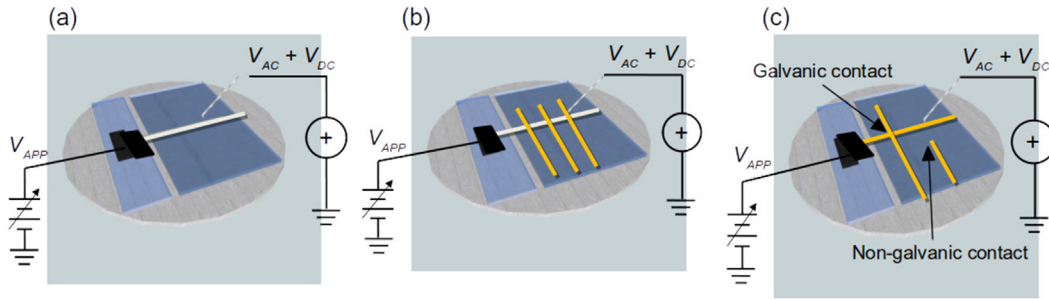


Fig. 1. Sample set-ups for the KPFM analyses. (a) Polarized single polyester fibre (P configuration), (b) Polarized polyester fibre in galvanic contact with conductive fibres (P + B configuration) and (c) polarized conductive fibre in galvanic contact or non-galvanic contact with conductive fibres (B + B configuration). Conductive stainless steel fibres are in yellow, white fibres are insulating polyester fibres; the black pads on the left are the contacts where the polarization bias V_{APP} was applied. The grey disk is an insulating support made of Teflon. The blue rectangles are pieces of double face adhesive tape. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

desorption events. In this case, a surface carrying an excess of negative charges, for instance, releases $[\text{OH}(\text{H}_2\text{O})_n]^-$ ions and/or adsorbs $[\text{H}(\text{H}_2\text{O})_n]^+$ ions. The ions are exchanged with the surrounding atmosphere and lead to a net decrease of the negative charge [27].

Second, charge decay may occur through the bulk of the dielectric material, a mechanism referred as diffusive transport in previous works [28,29]. These mechanisms are not easy to be distinguished since several physical processes may give similar results and can vary according to the experimental conditions and the charging methods. Furthermore, most of the studies realized up to now were done on the surface of polymer films at the macroscopic and mesoscopic levels. The systematic investigation of microscopic surface potential decay is thus needed to complement the existing theories.

Kelvin probe force microscopy (KPFM) was first reported in 1991 [30] and is widely used for measuring the distribution of surface potential and for the detection of charges on a wide range of materials under different experimental conditions, such as metals, semiconductors and insulating materials [31–34]. The technique uses a metal coated or doped silicon tip. When the tip is brought in close proximity with the measured surface, the Fermi levels of both materials align themselves generating a contact potential, called the surface contact potential difference ($V_{CPD} = \frac{1}{e}(W_t - W_s)$ with e the elementary charge ($1.609 \cdot 10^{-19}$ C) and W_t and W_s the work functions of the tip and sample materials respectively). This difference is compensated by an external applied potential, which enables the measurement of V_{CPD} . If a bias voltage is applied to the sample, the measured voltage will be equal to the sum of the sample bias voltage and the contact potential. The measured surface potential on conductive surfaces refers thus to the surface work function. However, on insulating surfaces, the interpretation of the KPFM signal is not straightforward. Generally, the surface charge density is difficult to derive directly from the measured surface potential values. However, in a first approximation, the charge density which is constant on an area large enough to be resolved by KPFM is proportional to the measured surface potential (V_s). Under these assumptions, the surface charge density σ ($\text{C}\cdot\text{m}^{-2}$) that is located on the insulating surface can be approximated using a capacitor equation [32,35].

$$\sigma(x, y) = \epsilon_r \epsilon_0 V_s(x, y) d_{ts}^{-1} \quad (1)$$

with ϵ_r the relative dielectric constant of the insulating surface layer, ϵ_0 , the vacuum dielectric permittivity and d_{ts} , the average tip-surface distance. Equation (1) comes from the fact that the charges induced in the probe by the applied voltage have to match the charges on the insulator surface in order to nullify the electrical force between the charged surface and the probe. On insulating surfaces, the absolute value of the charge density is still difficult to be derived. However, the charge density is proportional to the measured surface potential. In this context, KPFM has proven to be a useful tool to monitor the evolution of

surface charges on material surfaces [33,36–38]. This technique is thus expected to be able to monitor surface charge decay (charge transport and dissipation behaviours) not only on the surface of single fibres but also on the surface of contacted fibres.

In this paper, microscopic surface potential evolution measurements are realized by KPFM on the surface of isolated fibres or on the surface of fibres in the presence of another fibre put in galvanic or non-galvanic contact with the studied fibre. A detailed and systematic study is performed on different fibre configurations. The charge, discharge and charge transfer behaviours are discussed as a function of time and the applied polarization voltages.

2. Materials and methods

In this study, two kinds of fibres commercially available were used: insulating polyester fibres and conductive stainless steel fibres which brand name is Bekinox[®] produced by the company Bekaert in Belgium (both types of fibres were provided by Sioen Nordifa, Belgium). The fibres are used for the manufacture of antistatic filters for filtering different kinds of powders. The diameter of the stainless steel fibres varies between 7 and 13 μm , and that of polyester fibre varies between 10 and 20 μm . The fibres were stored under ambient conditions and analysed as-received without any surface treatment.

KPFM experiments were performed using a Picoplus 5500 atomic force microscope (Agilent Technologies) equipped with a scanner of maximum scanning area of $100 \times 100 \mu\text{m}^2$, with a MAC III AC module and an extender electronics module. Pointprobes probes coated with a layer of Pt/Ir on tip and detector sides were obtained from Nanosensors. The typical spring constant and resonance frequency of the cantilevers were $1.2\text{--}29 \text{ N m}^{-1}$ and $75\text{--}260 \text{ kHz}$, respectively.

The experimental set-up is presented on Fig. 1. Prior to performing the charge or discharge experiments, different thicknesses of Teflon supports were tested and the result showed that the Teflon support should be thicker than 3 mm in order to avoid noticeable charge leakages. A notch was made on the double-face adhesive tape to ensure that the bias voltage was applied only on one single fibre. The whole set-up was mounted in the environmental chamber of the AFM and was allowed to stabilize overnight. The surface potential was found to have a strong dependence on the humidity. Low humidity reduces the charge and discharge rate [32]. Therefore, the relative humidity was controlled in the environmental chamber containing the sample by using a saturated solution of potassium acetate. The relative humidity can be kept at 25% at a temperature around 22 $^\circ$ C.

Three sample configurations for KPFM measurements were used as presented in Fig. 1. Fig. 1(a) shows the configuration used to polarize a single isolated polyester fibre, hereinafter called the "P configuration". The bias voltage was applied on one end of the polyester fibre and the surface potential variation was measured at different positions on the

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