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Phenomenological model of wetting charged dielectric surfaces and its testing with plasma-treated polymer films and inflatable balloons

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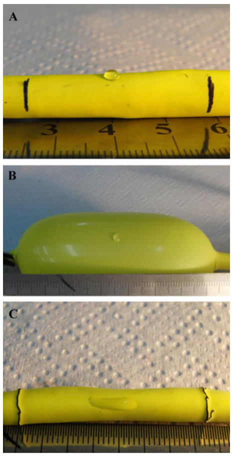
HIGHLIGHTS

- Wetting of charged surfaces is treated.
- Theory relating the change in the contact angle of charged solids to the surface charge density is introduced.
- Partial wetting becomes possible until the threshold density of the electrical charge is gained.
- The predictions of the theory are illustrated by plasma-treated polymer films and inflatable balloons.
- Deflating of plasma treated balloons enabled the increase in the surface charge density of latex.
- The increase in the surface charge density switched the wetting regime from partial to complete wetting.

GRAPHICAL ABSTRACT



Regimes of wetting of latex balloons. (A) Wetting of a non-treated balloon. The apparent contact angle is close to 90°. (B) Partial wetting of inflated plasma treated balloon. The apparent contact angle equals. (C) Complete wetting of the plasma treated deflated balloon.

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ABSTRACT

Plasma treatment of polymer films results in their electrical charging, which in turn gives rise to an increase in their surface energy. The process results in pronounced hydrophilization of the polymer surfaces. A phenomenological theory relating the change in the apparent contact angle of charged solids to the surface density of the electrical charge is introduced. Partial wetting, inherent for polymer films, becomes possible until the threshold surface density of the electrical charge is gained. The predictions of the theory are illustrated by plasma-treated polymer films and inflatable latex balloons. Deflating the plasma treated latex balloons resulted in an essential increase in the surface charge density of the latex. This increase switched the wetting regime from partial to complete wetting. The kinetics of hydrophobic recovery follows the kinetics of the electrical charge leakage from the surfaces of the plasma treated polymers. The characteristic time of the surface charge leakage coincides with the time scale of the decay of the electret response of plasma treated polymer films.

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1. Introduction

Wetting of charged surfaces has attracted the attention of researchers in the last decade [1–6]. Electrical charging of surfaces has an effect on contact angles [1,2,4], dynamics of the triple line [3,6] and other interfacial phenomena. The practical interest in the wetting of charged surfaces is based on the fact that they enable, with no mechanical parts, the control of liquid movement and/or a quick change of states of the system [4]. Molecular insights into the hydrophilicity of charged surfaces were discussed recently [1,5]. The majority of papers devoted to the interfacial properties of charged surfaces deal with conducting surfaces [4,7,8]. The main (Gibbs) equation relating the surface charge density σ to the surface tension γ, given by $\sigma = -\left(\frac{\partial\gamma}{\partial\varphi}\right)_{P,T}$ (where φ, P and T are the potential, pressure and temperature correspondingly) was derived for the conducting surfaces [9]. In contrast, our paper is devoted to charged dielectric materials (polymers).

Electrical charging of polymers takes place under plasma treatment (at low and atmospheric-pressure), which is widely used for the modification of surface properties of solid organic materials [10–16]. The plasma treatment creates a complex mixture of surface functionalities which influence surface physical and chemical properties; this results in a dramatic change in the wetting behavior of the surface [16–22]. Plasma treatment is accompanied by the trapping of plasma ions by a polymer substrate, resulting in its charging. The kinetic model of such charging, which predicts the surface density of an electrical charge supplied by plasma, was reported recently [23]. In the present paper, we propose a phenomenological model, relating the hydrophilization of a plasma-treated polymer surface to its charging. The model was verified with inflatable latex cylindrical balloons enabling the control of the surface charge density.

The pronounced hydrophilization of plasma-treated polymer surfaces is gradually lost with time. This process is called the hydrophobic recovery [22–26]. We relate the hydrophobic recovery to a temporal leakage of the electrical charge.

2. Experimental

We used the extruded polypropylene (PP) films with the roughness of the films established with AFM as 10–20 nm; for the AFM study a Park 5 M scanning probe microscope (Scientific Park Instruments) was used and latex-rubber balloons were electrically charged by a plasma unit (EQ-PDC-326 manufactured by MTI Co, USA). Dried compressed air was supplied by Oxygen & Argon Works, Ltd., Israel; moisture was less than 10 ppm, the concentration of oxygen was 20–22%.

Thoroughly cleaned PP film samples, with the dimensions of 25 × 25 mm and the thickness h of 25 μm, were exposed to an air radiofrequency (RF) plasma discharge under the following parameters: the plasma frequency was 13.56 MHz; the power was 18 W; the pressure was 1 Torr; the volume of the discharge chamber was 840 cm^3. The time span of irradiation was 15 s. The latex-rubber balloons were treated under the same parameters. The scheme of the experimental unit used for the plasma treatment of the PP films and latex-rubber balloons is depicted in Fig. 1.

The surface charge density of the PP was established with the electrostatic pendulum shown in Fig. 2a. The measurement of the angle α between the threads enabled the estimation of the surface charge density σ. The same method was applied for the estimation of the charge density of the latex balloons charged by plasma, as shown in Fig. 2b.

Apparent contact angles were established using the Ramé–Hart goniometer (Model 500). A number of film specimens were simultaneously plasma-treated; this enabled deposition of water droplets on the “freshly treated” portions of the substrates at fixed time intervals. Ten measurements were taken to establish mean apparent contact angles at ambient conditions. The kinetics of a hydrophobic recovery was studied by measuring apparent contact angles every 5 min during the first hour, every hour during the first five hours and every day during 3 days. Ten values of the apparent contact angles were taken on both sides of a droplet; the results were averaged.

The study of the influence of the surface charge density was performed with a self-made unit based on inflatable polyisoprene latex cylindrical balloons (Pioneer Balloon Company Qualatex, Canada). The images of the non-inflated and inflated balloons are supplied in Fig. 3.The thickness of the balloon wall was 250 ± 50 μm. We measured contact angles on a non-pumped and pumped balloon, and

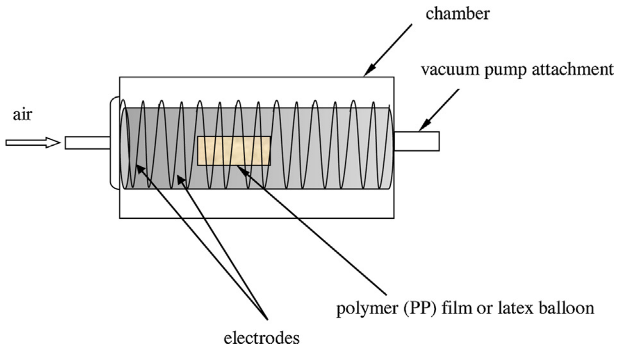

Fig. 1. Unit used for plasma charging of polymer films and latex balloons.

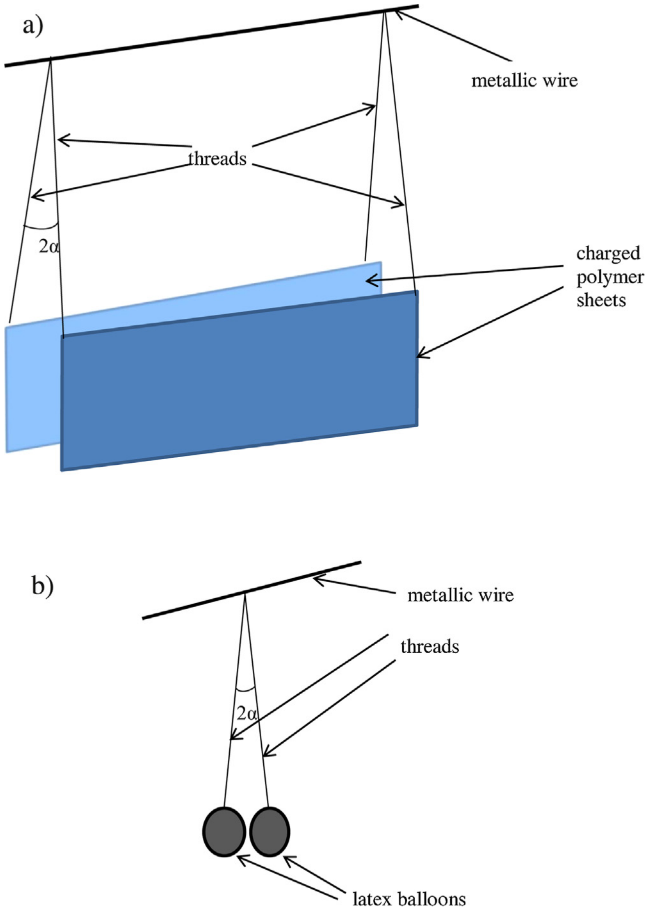

Fig. 2. Electrostatic pendulum used for the measurement of the surface charge density of polymers. (a) polypropylene (PP) sheets, (b) latex rubber balloons.