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Influence of corona poling on the electrostrictive behavior of cellular polypropylene films

J.W. Zhang[a,b,*], L. Lebrun[a], B. Guiffard[a,c], P.-J. Cottinet[a], R. Belouadah[a,d], D. Guyomar[a], L. Garbuio[a]

[a] Université de Lyon, INSA-Lyon, LGEF, EA 682, Batiment Gustave Ferrié, 8 rue de la Physique, F-69621, France
[b] Northeast Dianli University, 169 Changchun Road, 132012 Jilin City, China
[c] IETR UMR CNRS 6164, Université de Nantes, 2 rue de la Houssinière, BP 92208, F-44322 Nantes cedex 3, France
[d] Département de Physique, Université de M'sila, PB 116 Ichebilia – M'sila, 28200, Algeria

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ABSTRACT

In this study, a quadratic electric field dependence of the strain on the −30 kV corona-charged cellular polypropylene (PP) was observed, which was found to mainly originate from electrostriction after evaluation of Maxwell stress effect. The −30 kV-charged sample presented a maximal strain twice as high as that of the non-charged sample for the same applied electric field. Both the dielectric constant and apparent electrostrictive coefficient of cellular PP were also seen to increase after corona poling treatment. We investigated such higher electrostrictive response from the behavior of surface potential decay, the TSC current and the thermal properties. From TSC current curves, it was found that a certain amount of charges became injected into the film. And then, the total charge within the PP was calculated by integrating the TSC current, which provided a convincing evidence for enhanced electrostriction of studied polymer. In addition, from DSC analysis, it was demonstrated that the corona treatment increased the crystallinity of the cellular PP, which was also highly desirable for enhancing the electrostrictive response. Increase in the permittivity and strain was explained experimentally and mathematically by using the space-charge theory and a simplified model.

1. Introduction

Electroactive polymers present numerous advantages as compared to classical ferroelectric materials. They can be prepared at low cost, molded into various shapes and deposited on large surfaces. They are also lightweight and can generate high levels of strain [1–3]. Recently, new types of polymer composites, obtained by filling a polymeric matrix with conductive nanofillers (i.e., carbon nanopowder, carbon nanotubes, etc.), have been synthesized. These composites exhibit large strains at medium electric fields and consequently appear to be promising electroactive materials for actuation with high electrostrictive coefficients [1,2]. As these outstanding properties seem to be linked to the space-charge distribution [4], it seems to be interesting to evaluate the actuation performance of a dielectric material in which only electrical charges have been injected instead of filling it with nano-objects.

The most well-known technique for injecting charges is the high-voltage corona treatment. The sample is placed under a metallic grid onto which a negative potential is applied. A high voltage generator is connected to metallic needles in order to inject charges within the polymer. Various parameters (temperature, grid voltage, position of the needles) control the quantity of the injected charges and their profile within the materials. Several papers have described this process and the equipment in detail [5–7].

Beyond the various available materials, cellular polypropylene (PP) is a well known polymer for its ability to store electrical charge when subjected to the corona poling and for having ferroelectric-like properties (like remnant electrical field-induced polarization and converse piezoelectric effect, i.e. strain directly proportional to the electric field) caused by charged lens-like voids which are responsible for a strong anisotropy within the polymer. It has therefore been given the name ferroelectret [8–13]. However, few studies have been done on how injected charge affects electrostriction property of charged cellular PP, which corresponds to a strain proportional to the square of the electric field.

Negative corona-charged PP has been widely studied [14–17]. By using the Thermal Stimulated Current (TSC) method, de-trapped charges and a relaxation of the polarization have been observed by Ono et al. [5]. Furthermore, the Laser Induced Pressure Pulse (LIPP) technique has also been used in former investigations for displaying the charge distribution [5]. By integration of the TSC current, the quantity of charges can be calculated.

The goal has been to, for the first time, evaluate the effect of charge injection on the apparent electrostrictive coefficient of cellular PP by combining surface voltage measurements, and the TSC

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* Corresponding author at: Bat. Gustave Ferrié, 8 rue de la Physique, F-69621, Villeurbanne Cedex, France. Tel.: +33 472438077; fax: +33 472438874.
E-mail address: jiawei.zhang@insa-lyon.fr (J.W. Zhang).

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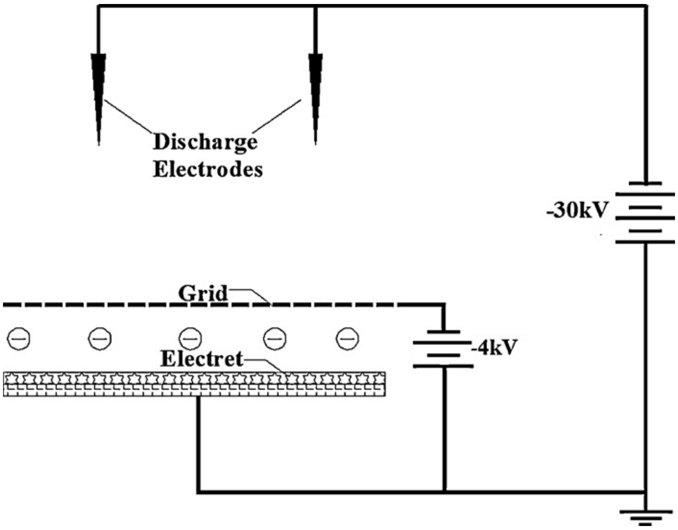

Fig. 1. The corona discharge setup.

and DSC methods which can give the information on stability and quantity of injected charge, as well as crystallinity, and evaluate enhanced electrostrictive response by these methods. In order to explore the application potential of such a readily manufacturable polymer, the effect of its surface roughness on the charge injection was also explored, which can influence the charge injection of cellular polymer and its electrostrictive response.

2. Tested samples and setup of the experiments

The chosen samples, denoted PQ50 whose thickness and density are 50 μm and 600 kg/m^3 respectively, were prepared by Sodinor Company (France). Cellular polypropylene films (4 cm × 4 cm) were charged using a corona triode, which is schematically presented in Fig. 1.

The charged films were coated with a gold electrode on one surface (20 nm thick) under high vacuum by a High Resolution Sputter Coater (208 HR, Cressington). With a corona triode, the electrical charges were injected for a duration of 10 min through the non-metalized surface of the samples which were placed under a stainless grid (size of mesh screen is 150 μm) in order to maintain a uniform surface potential. With the aim of investigating the charge storage performance and its influence on the electrostrictive performance of fully charged cellular PP, the corona voltages were kept at −30 kV and a grid voltage of −4 kV was employed.

2.1. Surface potential measurement

Surface potential is one of the criteria to estimate charge-retaining ability of the polymer. In order to observe its charge-decay tendency after corona poling, an Electrostatic Voltmeter (Model542 TREK) was utilized to measure the surface potential of the samples. Immediately following the corona treatment, the surface potential decay of the charged samples was recorded with the help of an oscilloscope (DSO6034A Agilent).

2.2. TSC measurement

TSC measurements were performed in order to investigate the exact quantity of charge stored on the surface of and within the cellular PP. For these TSC experiments, a charged sample was placed in a test chamber with temperature control (Chamber VT7004, Vötsch Industrietechnik). As shown in Fig. 2, the two-surfaces-electroded sample was sandwiched between two copper plates, short-circuited and maintained at 23 °C for one hour in order to release the surface charge, after which the temperature was linearly increased from 23 °C to 140 °C at a rate of 5 °C/min [5,12].

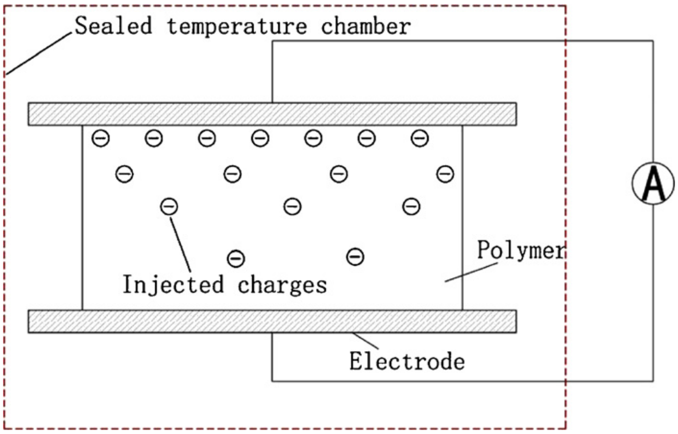

Fig. 2. The experimental process of the TSC technique.

The TSC current signal was measured with the help of a current amplifier (Keithley 428). In the meantime, the over-all thermal-current spectrum of the tested sample was registered by a data acquisition recorder (BD300 Series Kipp & Zonen Vötsch Industrietechnik).

The total charge Q_{corona} within the PP was calculated by integrating the TSC current, i_{tsc}, according to Eq. (1):

$$Q_{corona} = \int_0^t i_{tsc}dt \tag{1}$$

2.3. DSC measurement

Differential Scanning Calorimetry (DSC) is a useful tool for measuring heat capacity variations induced by phase transitions: i.e. melting, glass transition or crystallization [18]. The samples were placed in a closed aluminum crucible in the DSC equipment (DSC 131 evo Setaram), where they were heated from 23 °C to 200 °C and cooled down to 23 °C at a controlled rate of 10 °C/min. Two thermal cycles have been successively applied to the charged cellular PP. The heat flow was recorded synchronously by a computer connected to the DSC equipment.

2.4. Electrostrictive coefficient measurement and polarization measurement

As shown in Fig. 3, the strain versus electric field was measured with the help of a non-contact capacitive measurement sensor (FOGALE MC 940) on disc-shaped samples with a precision on the order of 10 nm. Because PP were elastically much softer than ceramics and the samples were made into very thin films, great care must be taken in the strain measurements of PP to ensure the accuracy of the data when applied an electric field on it. For such soft film flexure motion and mechanical clamping of a sample are two major causes of errors in the strain measurements. The film samples were placed on horizontal stainless steel discs (20 mm in diameter) in order to avoid measuring a parasitic flexure motion, and a second brass disc positioned on the top of the film rendered it possible to apply a bipolar electric field. The total weight of piece 2, 3 and 4 shown in Fig. 3 was 5 g (equivalent to 156 Pa) which was a suitable small stress, in order to avoid clamping of the sample. The sample was subjected to electric field with the help of a waveform generator (Agilent 33220A) for which the output was amplified through a