Multifractal Image Analysis of Electrostatic Surface Microdischarges

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The multifractal image analysis of Lichtenberg figures has confirrmed a self- similar arrangement of surface streamers belonging to the special case of electrostatic separation discharges propagating along a surface of polymeric dielectrics.

Keywords: Microdischarges, random processes, multifractals, electrets.

1 Introduction

Electrostatic discharges arising during separation of a charged sheet of a highly resistive material from a grounded object often assume the form of surface discharges. In such cases charge carriers are forced to propagate along a highly resistive dielectric surface where they are trapped and create latent invisible tracks which can be visualized by means of the well-known powder technique. The visible powder tracks called Lichtenberg figures [1] have been used many times [2–11] to study gaseous discharges on the surface of dielectrics.

The traditional experimental arrangement for studying surface discharges in the form of Lichtenberg figures consists of a point-to-plane electrode system and employs short voltage pulses in the micro- or nanosecond time scale. Our experimental arrangement differs somewhat from the traditional arrangement since the subject of a present investigation is not classical corona discharges but microscopic electrostatic discharges occurring between a charged dielectric surface and a grounded metallic electrode. These microdischarges appear in the narrow wedge-shaped air gap when the dielectric is separating from the electrode.

The morphology of Lichtenberg figures was a subject of interest many times in the past. With the advent of fractal geometry morphological studies became more sophisticated and more exact. The pioneering work of Niemeyer, Pietronero and Wiesmann [6] showed that a random structure of positive corona streamers form a fractal patterns on the dielectric surface and that these patterns can be modeled on a computer. These facts have been verified later many times by other authors [9, 10, 11–18].

This paper analyses the Lichtenberg figures created by electrostatic separation discharges. The general multifractal formalism [19–41] has been used to perform the multifractal image analysis of surface discharge patterns: the discharge figures have been scanned with the resolution of 120 dpi and their digital images have been processed, i.e., the channel structure has been extracted from the background and then subjected to software multifractal analysis.

2 Experimental arrangement

The experimental arrangement consists of a sandwiched plane-to-plane electrode system and DC high voltage applied for various time periods ranging from several minutes to many hours. The polyethyleneterephthalate (PET) sheets 0.180 mm thick were pressed between a bronze electrodes of diameters $\phi_1 = 20$ mm and $\phi_2 = 40$ mm. The smaller electrode was loaded with the negative electric potential of –8.5 kV while the larger electrode was grounded. This resembles the arrangement used for poling electrets, and the chosen highly resistive dielectric samples – PET sheets – are also good electrets. However, charging the samples is not performed at higher temperatures as with usual electret poling but at common room temperatures. When the sheet of polymer is separated from the grounded plane electrode, the electrostatic discharges 'draw' latent Lichtenberg figures on the surface of the polymer.

2.1 Computational model

Since the 1980s the multifractal calculations [15–19] have been employed as the basic tool for morphological studies of complex objects embedded mostly in Euclidean space. For multifractal analysis the Euclidean space of the topological dimension E is partitioned into an E-dimensional grid whose basic cell is of a linear size ε (arrangement necessary for the box-counting method). One of the topological partition sums used in this field is defined by the probability moments

$$m_q(\varepsilon, q) = \sum_{i=1}^{I} p_i^q(\varepsilon)\,, \quad p_i(\varepsilon) = \left(\frac{n_i}{N}\right),$$
$$\sum_{i=1}^{I} p_i(\varepsilon) = 1\,, \quad q \in (-\infty, +\infty)\,. \tag{1}$$

The symbol n_i represents the number of points in the i-th cell and N is the number of all points of the object studied.

The goal of multifractal analysis is to determine one of the three multifractal spectra. The most frequently used spectrum is that of generalized dimensions D_q

$$D_q = \lim_{q^* \to q} \frac{\partial \ln m(\varepsilon, q)}{(q^* - 1)\, \partial \ln \varepsilon}\,. \tag{2}$$

The present fractal objects are in the form of graphical bitmap files created by digitizing the pictures. The plane of graphical pixels (points) representing the fractal object is covered with a two-dimensional grid whose basic cell is of linear size ε pixels. Using this grid the partition sum (1) is computed. Since the covering of the plane with a grid is arbitrary and the position of the grid should not infuence the results, we used several positions of the grid to find the average value of the partition sum $M_q(\varepsilon, q)$. For each ε-grid there are ε^2 independent coverings generated by shifting the grid origin within the first ε-cell

$$M_q(\varepsilon) = \frac{1}{\varepsilon^2} \sum_{j=1}^{\varepsilon^2} m_j(\varepsilon, q) \ . \tag{3}$$

Such a procedure requires the fractal set to be embedded in a larger grid that allows one to move the origin without losing of any part of the fractal object. The averages $M_q(\varepsilon)$ are estimated for a series of ε-grids and the slopes in the bi-logarithmic plot ($\ln \varepsilon$, $\ln M_q(\varepsilon)$) are calculated using the linear regression method. These slopes divided by the corresponding $(q-1)$ values represent the generalized dimensions D_q. Different D_q values for an analyzed object indicate multifractal behavior while identical values signify simple fractal features.

The algorithm described above has been implemented by means of the software tool Delphi. The created computer program MULTIFRAN is able to run on the NT system or on Windows.

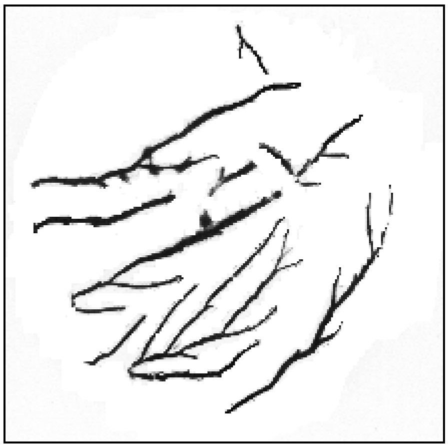

Fig. 2: Surface streamers extracted from Fig. 1

3 Results and discussion

Figs. 1, 2 show surface structures 'drawn' by electrostatic separation microdischarges appearing after the electret poling (74.5 hours at 8.5 kV) when the saturated electret state has been reached.

To our knowledge, the first author to report the channel structure of electrostatic separation discharges on the surface of polyethyleneterephthalate was Bertain [3]. She presented a picture (Fig.7 in [3]) showing the 'charge distribution obtained when a negatively charged foil of Mylar is removed far from an earthed plate'. The clearly depicted and ramified channel structure is very similar to that in our Fig. 1. Similar pictures are also available in the detailed study of separation discharges published by Takahashi, Fuji, Wakabayashi, Hirano and Kobayashi [8].

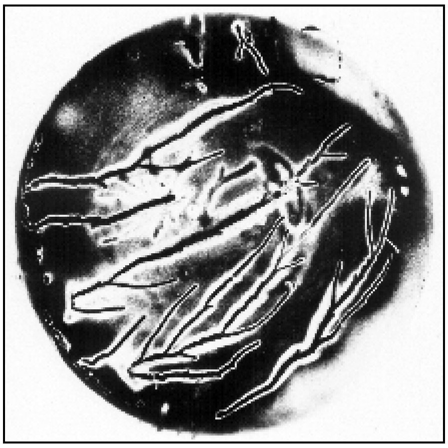

Fig. 1: Electrostatic discharge structure for poling time 1min. and voltage −8.5kV

A characteristic feature in the morphology of a positive streamer channel is their ramification (Fig. 2). At first sight it apparent that the branching of the surface channels determines the geometry of the structure. An abundant ramification, when the branches thoroughly fill the surface, leads to a geometrical structure whose dimension D will approach that of a plane ($D = 2$). On the other hand, at poor ramification, when branches arise sparcely and the structure resembles a group of linear simple channels, the corresponding dimension can be expected to be close to that of a line $D_{\text{lin}} = 1$. If no surface streamer channels appear but only point-like microdischarge spots are developed, dimension D will approach that of a point, i.e, $D_{\text{point}} = 0$. Therefore, the interval $\langle 0, 2\rangle$ represents all possible values of dimensions D of the surface positive streamers. The actual geometrical dimension D for a given structure can be obtained from the multifractal analysis in terms of the Hausdor-Besicovitch dimension D_0 [45]. In order to analyse our surface streamers it was necessary to extract the channel structure from the background of the remanent electret surface charge (Fig. 2).

The results of the corresponding multifractal analysis have shown that the studied structures manifest fractal rather than multifractal features so that the spectrum of the generalized dimensions D_q reduces to a single representative value D for all q. The actual value of dimension D for the structure presented in Fig. 2 is 1.45 ± 0.2.

The first authors to recognize possible fractal features of a surface discharge channel structure and tried to estimate its fractal dimension were Niemeyer, Pietronero and Wiesmann [6]. They determined the value $D = 1.7$ for their surface corona streamers. This higher value of dimension corresponds to a more ramified channel structure, which can be easily checked by visual inspection of their Fig. 1 in [6].

Many followers appeared in the field of computer simulations of discharge channel structures [12–18]. The dimensions obtained from these simulations show a large variety of values influenced by the chosen model parameters: Structures can be found with restricted ramification [10], i.e., with a lower dimension $D \sim 1.46$ [10] which is close to our value $D = 1.45$ or more ramified structures $D \sim 1.75$, [10] or even very branched structures $D \sim 1.8$–1.96 [6, 14]. Although much work in this field has been done, one important question still remains: what physical parameters influence ramification of the channel structure and exactly what mechanisms participate.

The original computer model of Niemeyer, Pietronero and Wiesmann [6] solved the problem of ramification by introducing the 'growth' probability p dependent on a local electric field E

$$p \sim E^{\eta}, \tag{4}$$

where η is a model parameter. In the sequence of simplifying simulation steps the dimension D of the resulting structure is dependent on the only model parameter η, i.e, $D(\eta)$, although there is experimental evidence [3], [8] that branching depends on more than one parameter: the thickness ratio between the discharge gap and the dielectric layer, electronegativity of the used gas and the chosen external (global) voltage, to mention some of them. The dependence on external voltage for the case of our surface electrostatic separation discharges actually means dependence on the remanent electret surface charge density. This study should be followed up by verification this dependence by performing the analysis at various poling potentials.

A fractal dimension seems to be a characteristic parameter not only for the amplitude statistics [46] used for non-destructive testing of partial microdischarges in the field of high voltage technology but it seems to be also a promissing candidate for assessing electret charge saturation, which has been indicated by our experiments. Further study of this problem is in progress and a following report on the subject is in preparation.

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