Fractality of Electrostatic Microdischarges on the Surface of Polymers

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Ramified Lichtenberg figures caused by electrostatic microdischarges on the surface of polymeric polyethylene terephthalate have been studied. They occurred in consequence of the previous electret forming of the polymeric sheets and were initiated in the air gap between the grounded electrode and the polymeric sheets. Multifractal image analysis was used to determine the fractal dimensions of the Lichtenberg patterns in dependence on the loading voltages used for electret forming.

Keywords: Electrostatic microdischarges, Lichtenberg figures, multifractal formalism, fractal dimension, electret saturated states.

1 Introduction

Electrostatic erosive microdischarges accompany triboelectric charging of various objects during their industrial production as well as during their use in everyday life. It is especially polymeric solids that are liable to surface charge accumulation to such an extent that they can even cause electric breakdown of an adjacent gas environment. Usually, this phenomenon is undesirable because of its disruptive effects in industrial production, laboratory research, and civil working activities. The study of these surface microdischarges is therefore useful from various points of view.

Surface microdischarges often assume the form of branched channel structures whose particular channels represent streamer discharges propagated along the surface of the object. Such branched patterns can be visualised by using photographic or powder techniques. These visible tracks are called Lichtenberg figures and have often been used to study gaseous discharges on the surface of dielectrics [1–6].

To visualise Lichtenberg figures, it was necessary to chose a transparent, highly resistive material in the form of thin layers (foils). Polyethylene terephthalate (PET) seems to be a convenient material for such a purpose. It is in broad use in industrial, academic, as well as civil applications. PET is a hard, stiff, strong, dimensionally stable material that absorbs very little water. It has good gas barrier properties and good chemical resistance except to alkalis. Its crystallinity varies from amorphous to fairly high crystalline; it can be highly transparent and colourless but thicker sections are usually opaque. It is widely known as a biaxially oriented and thermally stabilised film. It is produced in various modifications according to its destination: Mylar® films are used for capacitors, graphics, photographic film base, recoding tapes, etc. Other modifications are used as fibres in a wide range of textiles (Dacron®, Trevira®, Tyrelene®) or in the food industry (PET bottles) and the electrical industry (for insulation). Nevertheless, its probably most important feature, investigated intensively in academic research, is the ability to conserve an electric charge for a very long time. This feature ranks it among the high-quality electrets.

The charging of electrets (forming electret states) is performed in various ways, the most frequent of which involves inserting an electret foil between two parallel electrodes loaded by a sufficiently high electric field. The process of electret forming may be facilitated by increasing the ambient temperature up to the point of glass transition of the polymer (~85 °C for PET). However, a good electret state can be reached at normal room temperature, too. As soon as the charged electret foil is separated from the electrode system, electrostatic microdischarges may cross the air gap between the charged foil and the grounded electrode to neutralise the electret surface charge. In this way the latent Lichtenberg figures are drawn into the background electret charge. These structures may be visualised by using the powder technique and digital projection. After digital filtering of the background electret charge, only the branched patterns of the streamer channels remain on the surface (Figs. 1–3) and these filtered structures (true Lichtenberg figures) may by studied from the morphological point of view. For example, seeking for the relation between the fractal dimension of Lichtenberg figures and the stage of initial electret state, it is possible to answer the question whether the morphology of the Lichtenberg figures is a direct consequence of the initial electret state or whether they are caused by a purely stochastic process.

2 Experimental arrangement

Highly resistive polymeric sheets of amorphous polyethylene terephthalate were carefully cleaned with ethanol and then inserted between two short-circuited copper plates for 24 hours to eliminate surface charges. The PET sheets 0.180 mm in thickness were pressed between flat 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. The time application of HV was chosen in the intervals of several minutes up to hundreds of hours.

3 Multifractal analysis

Although the method of multifractal analysis has been described in our preceding paper in this issue, yet, we would like to repeat main features of the method.

Multifractal calculations [7–11] have represented a fundamental aid for geometrical investigations of complex disordered systems since the early eighties. Multifractal analysis – in the form of box-counting method – assumes the studied complex system to be embedded in E-dimensional Euclidean space. This Euclidean space is partitioned into a grid with the

same dimension E. The basic cell of the grid is of a linear size ε. Using probability moments p_i a partition sum m_q is defined on the grid

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

where n_i is a number of points in the i-th cell and N represents a number of all points of the complex system.

The spectrum of generalised dimensions D_q is usually used for the purpose of the analysis

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

The complex systems under investigation are in the form of graphical bitmap files that were created by means of a scanner. In this way the object is converted into a set of graphical pixels that are covered with a two-dimensional grid with the basic cell ε. On this grid the partition sum (1) is determined. To avoid a dependence on the orientation of the grid, several positions of the grid in the Euclidean space are realised and an average partition sum $M_q = (\varepsilon, q)$ is calculated

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

The averages $M_q(\varepsilon)$ are determined for a series of ε-grids and the slopes within the coordinate system $(\ln \varepsilon, \ln M_q(\varepsilon))$ are estimated using the linear regression. The slopes divided by $(q-1)$ give the generalised dimensions D_q. An object which produces identical D_q for all q is called 'monofractal' while different D_q–values indicate a 'multifractal' object.

3 Results and discussion

In this study 150 PET samples were investigated. Three different forming voltages (8 kV, 4 kV, 2 kV) and ten different forming intervals (480 min., 240 min., 120 min., 60 min., 30 min., 15 min., 5 min., 1 min., 0.5 min., 0.25 min.) were used to create corresponding electret states each of which was represented mostly by five PET samples. However, some of the samples were removed from the statistical ensemble because their Lichtenberg structures were not developed or because of other experimental problems. The remaining 110 samples were analysed and their fractal dimensions de-

Table 1: Results of experiments

	Dimensions D		
t/min.	8 kV	4 kV	2 kV
480	–	1.384	1.253
240	–	1.387	1.404
120	1.404	1.296	1.205
60	1.505	–	1.260
30	1.522	1.214	1.133
15	1.613	1.175	1.214
5	1.514	1.267	1.098
1	1.494	1.268	discharges disappear
0.5	1.290	1.204	
	–	1.085	
Average dimensions D_s of saturated states and their probability errors			
	1.477 ± 0.026	1.253 ± 0.022	1.224 ± 0.025

A) B)

Fig. 1: Lichtenberg figures generated at 8 kV and 30 min., ($D = 1.486$, sample no. 27)

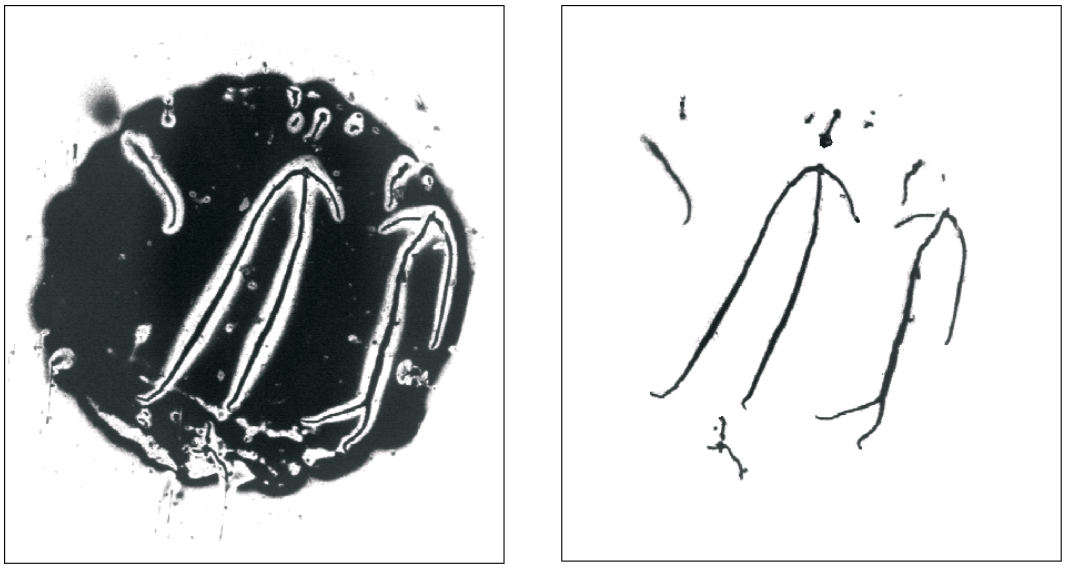

Fig. 2: Lichtenberg figures generated at 4 kV and 30 min., ($D = 1.246$, sample no. 86)

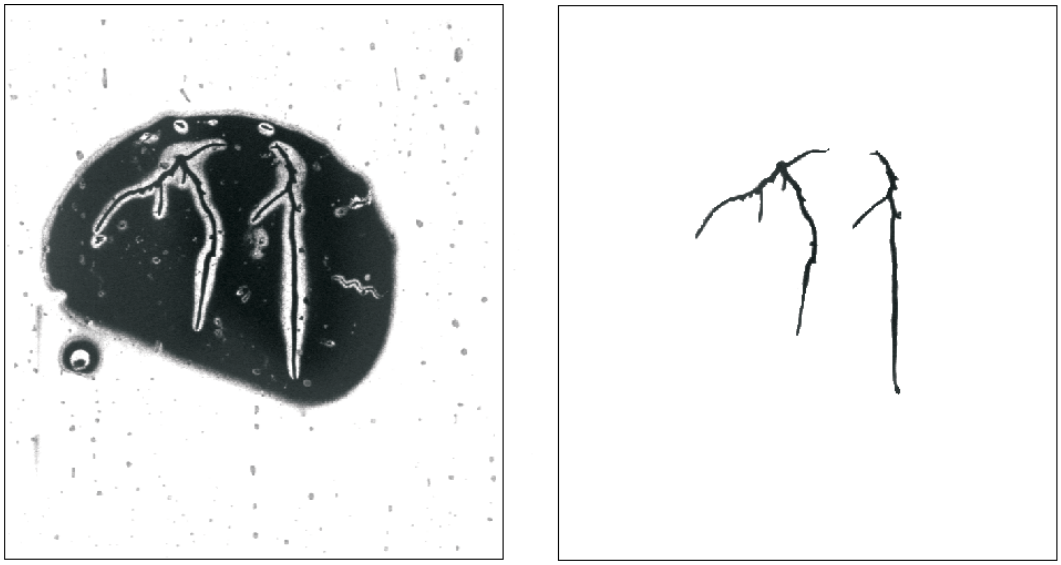

Fig. 3: Lichtenberg figures generated at 2 kV and 60 min., ($D = 1.225$, sample no. 131)

termined. The resulting Hausdorf-Besicovitch dimensions of the Lichtenberg figures generated from the saturated electret states are listed in Table 1. The experiments were performed at normal atmospheric conditions with small variations (less than 5 %) around the average values: $p_2 = 102.19$ kPa, $\Theta_0 = 24.31$ °C, $\varphi_0 = 69.7$ % RH. The processing of one typical sample (cleaning, conditioning, forming, separating, developing, digitising, filtering, analysing) took about 30 hours.

Comparing our experimental conditions (forming electric fields and times) with those of normally used [12], it is possible to assume that for all our combinations of voltages and times (Table 1) the *saturated* electret states were reached. These *saturated* electret states are dependent only on forming voltages U and not on times t, since the chosen times ($t \geq 0.25$min.) are sufficiently long for reaching electret saturation with PET samples at 2 kV and higher voltages ($U \geq 2$ kV).

Therefore, if the fractal dimension D of the Lichtenberg figures risen from the *saturated* electret states is dependent on the *stage of saturation*, then the fractal dimension D should be dependent on the forming voltages U and has to show an increasing dependence $D(U)$. This hypothesis has proved to be sound and is illustrated by Figs. 4–6 in which the increasing linear dependence $D = aU + b$ is well recognisable. In addition, if our forming times are sufficiently long for reaching saturation states, the average dimensions D_s calculated from those belonging to the same columns of Table 1, i.e. for the voltages of 8 kV, 4 kV, and 2 kV (dimensions 1.477, 1.253 and 1.223), also have to be an increasing function of voltage

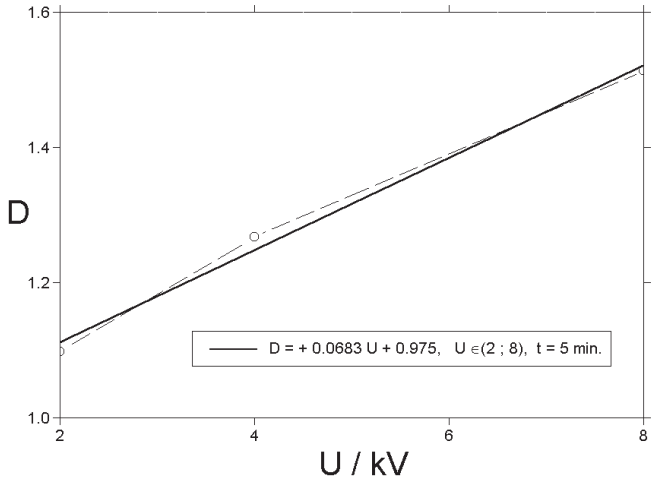

Fig. 4: The fractal dimesion D in dependence on forming voltages U for forming time $t = 5$ min.

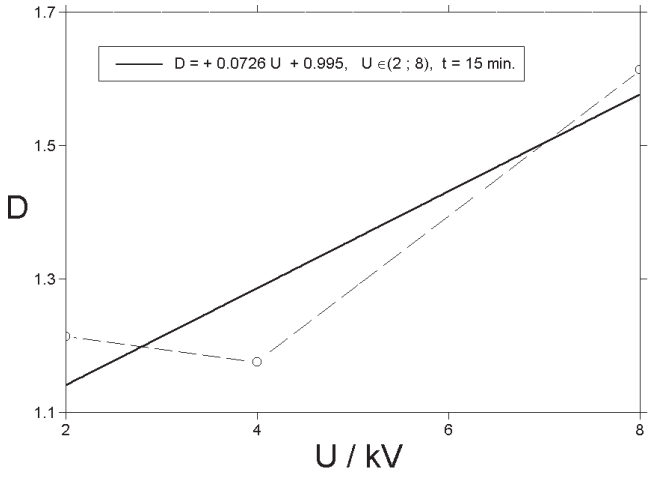

Fig. 5: The fractal dimension D in dependence on forming voltages U for forming time $t = 15$ min.

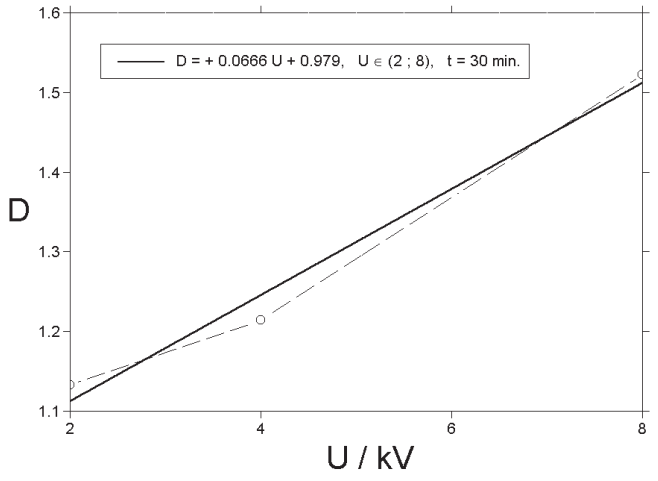

Fig. 6: The fractal dimension D in dependence on forming voltages U for forming time $t = 30$ min.

$D_s(U)$, which is documented in Fig. 7. In addition, this trend of branching structures with increasing voltages is visible in Figs. 1–3 which present three different Lichtenberg figures in dependence on voltage (the forming times were chosen suffi-

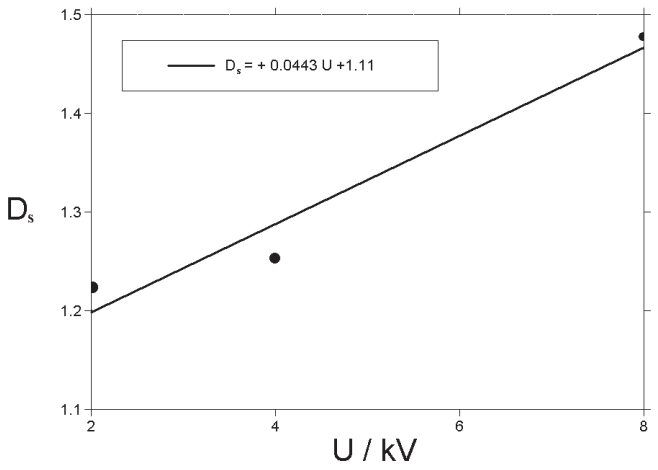

Fig. 7: The average fractal dimension D_s in dependence on forming voltages U

ciently long to reach saturated electret states for the respective voltages). All these experimental findings lead us to the opinion that the morphology of Lichtenberg figures (i.e. their fractal dimension) is not a consequence of purely stochastic processes but rather it is dependent on the stage of the electret saturation which is determined solely by the forming voltages U, provided sufficiently long forming times have been used.

4 Conclusions

The performed experiments have shown that the branching of Lichtenberg figures caused by electrostatic microdischarges on the surface of polyethylene terephthalate is not quite a stochastic phenomenon but rather a process that is governed by the stage of electret forming. Since the attainability of a *saturated* electret state is dependent on the forming voltage U and time t, the fractal dimension D of the corresponding Lichtenberg figures should be a function of these parameters, i.e. $D(U, t)$. Nevertheless, for *sufficiently long times* $t > t_{\min}$ the dimension D is a function of voltage only, i.e. $D(U)$. It seems to be natural that the $D(U)$ function cannot increase its values to infinity but rather it should be restricted by some maximum $D_{\max}$ and minimum $D_{\min}$ values characterising a particular electret ($0 \le D_{\min} < D_{\max} \le 2$). However, a verification of this idea would require further experiments.

Acknowledgment

This work was supported by the Grant Agency of the Czech Republic under the Grant No. 202/03/0011.

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