Optimization of continuous triboelectrification process for polymeric materials in dry contact

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Abstract. Triboelectrification (i.e., generation of electric charge by friction between two materials) is a complex process. Besides the nature and condition of the surfaces in contact, several factors can have an influence on charge generation: pressure load and relative velocity between the two bodies, number of friction cycles, ambient temperature and humidity, condition and type of material surface. This paper aims at demonstrating that associating the experimental response surface methodology and genetic algorithms is an effective technique for the optimisation of triboelectrification process. The quadratic model derived from the experiments is used in a genetic algorithm program to find the optimal combination of factor values (10 sliding cycles; normal force: 10 N; sliding speed: 55 mm/s) that maximize the average potential at the surface of the tribocharged materials: -1633 V. A final experiment confirmed the prediction of the genetic algorithm. The conclusions of this experimental study can be applied to the optimisation of industrial triboelectrification processes, and contribute to the reduction of the related maintenance, energy and raw-material costs.

1. Introduction

Electric charge generation by frictional contact between two bodies is a complex process, the outcome of which is affected by many factors, namely: normal force, number of friction cycles, friction velocity, ambient temperature and humidity, surface condition and nature of the materials in contact.

The purpose of the present work is to determine the optimal values of these factors, so that to obtain maximum electrical charge, evenly distributed on the contact surfaces [1-5]. From a mechanical point of view, frictional contact is highly correlated with wear, load, number of sliding cycles and temperature. Changes in one or more of these factors will alter the condition of the surface of the material and indirectly affect the outcome of the electrification process [6-11].

In the present paper, the response surface methodology (RSM) is used for experimental modelling of the process. A quadratic polynomial model is obtained by means of a central composite face-centred (CCF) experimental design [12-14], performed on a laboratory bench designed for testing translational tribocharging [15-17]. The distribution of charge is evaluated by measuring the electric potential at the surface of the samples, with the auto-compensated induction probe of an electrostatic voltmeter, in a room with controllable temperature and humidity.
2. Materials and methods

Acrylonitrile butadiene styrene (ABS) as top sample with the dimensions of 5 mm x 15 mm x 100 mm and Polyvinyl chloride (PVC) as bottom sample, 5 mm x 50 mm x 180 mm, are employed.

The residual charge at the surface of these samples is neutralized using a commercial ionizing system (electrode ECA 88 BS and high-voltage supply SC 04 B, 5 kV, 7 mA, manufacturer: ELCOWA, Mulhouse, France).

Triboelectrification is done using a custom-designed experimental bench [15] to generate the electric charge by friction between a pair of samples (1) and (2), in conformal contact (figure 1). The back-and-forth sliding motion of the bottom sample with respect to the top sample is controlled by a reversible variable speed electric motor drive. The relative velocity between the bodies in conformal contact can be varied between 55 and 275 mm/s, with the amplitude of the strokes ranging from 36 to 55 mm. The top sample holder (4) is fixed in a vertical guiding system, connected with an adjustable force arm. The normal contact force can be adjusted between 1 and 10 N. This triboelectric laboratory bench enables the control of several factors that influence the electrostatic charge generation: polymer rubbing speed, contact force, and number of friction cycles [15-17].

Mapping of the electric potential at the surface of the tribocharged sample, disposed on grounded plate, is made with an auto-compensated induction probe (model 3450, TREK Inc.), connected to an electrostatic voltmeter (model 341B, TREK Inc.). A computer-controlled x-y positioning system moves the sample with respect to the probe. Thus, the measurements are carried out in 95 points, which reflect the electric potential on the sample entire surface (figure 2). The distance between two points is 10 mm. The probe is at rest with respect to the sample, at the moment when the result of the measurement is recorded (figure 3). Surface temperature is observed with a thermal camera FLIR E60 to ensure that the requirement of uniform rubbing contact pressure has been respected (figure 4).

![Figure 1. Schematic representation of the rubbing process: (1) bottom sample; (2) top sample; (3) bottom sample holder; (4) top sample holder.](image1)

![Figure 2. Positions of the points in which the electric potential is measured at the surface of a bottom sample.](image2)

![Figure 3. Surface potential cartography of polymer sample type B (bottom).](image3)

![Figure 4. Surface temperature cartography of sample type B (bottom).](image4)
The factors under study in this experiment are the following: number of tribocharging cycles (10, 55, and 100), normal force applied on type B sample (2 N, 6 N, and 10 N) and frequency of back- and-forth sliding motion (0.5 Hz, which corresponds to a sliding speed of 55 mm/s), 1.5 Hz or 165 mm/s, and 2.5 Hz or 275 mm/s). The responses are: average surface electric potential ($V_{AVG}$), standard deviation of surface potential ($\sigma_V$) and temperature increase during tribocharging ($\Delta temp$). Response Surface Methodology (RSM) recommends the use of a Central Composite Face-Centered (CCF) experimental design as plotted in figure 5. The quadratic models that can be obtained with this experimental design are flexible and can mimic many different types of response function.

![Figure 5. Schematic representation of the CCF experimental design for three factors.](image)

The objective is to simultaneously maximize $V_{AVG}$, minimize $\sigma_V$ and minimize $\Delta temp$. Genetic Algorithm is chosen as optimization method. The association of this method with the Response Surface Methodology is expected to be an efficient way to find the optimal values of the three control factors of the triboelectrification process [18-21].

3. Results and Discussion

3.1. Surface potential mapping

The electric potential is mapped for each of the 17 experiments of the CCF design recommended by the response surface methodology. The experimental data plotted in figure 6, for instance, show that using maximum sliding speed leads to higher uniformity of electric surface potential.

![Figure 6. Surface potential mapping: (a) 10 Cycle, 10 N, 2.5 Hz; (b) 10 Cycle, 10 N, 0.5 Hz.](image)
Figure 7. MODDE 5.0 analysis of the experimental models; (a) Summary of fit plot; (b) Coefficient plot of $V_{AVG}$ function; (c) Coefficient plot of $\sigma_V$ function; (d) Coefficient plot of $\Delta temp$ function.

The $R^2$ index for each response function is 0.99, which means that the regression model appropriately fit the raw data. The predictive power of the model is also satisfactory: indexes $Q^2$ for $V_{AVG}$, $\sigma_V$ and $\Delta temp$ are respectively 0.90, 0.88 and 0.79.

The coefficient plot in figure 7 b shows that the normal force has a major impact on the surface potential. The normal force and number of tribocharging cycles have a significant effect on the $\sigma_V$ response function (figure 7 c). This means that the non-uniformity of the surface potential (and hence of the respective electric charge) increases with the normal force and the number of tribocharging
cycles. The latter factor is the most influential on surface temperature (figure 7 d). The response surface models fit to \( V_{AVG} \), \( \sigma_V \), and \( \Delta temp \) are:

\[
V_{AVG} = -616 + 46 \times Cyc - 468 \times NFo - 99 \times Fre - 119 \times NFo \times NFo + 92 \times Cyc \times Fre
\]

\[
\sigma_V = 1740 + 282 \times Cyc + 332 \times NFo - 72 \times Fre - 92 \times Cyc \times Cyc - 288 \times NFo \times NFo - 191 \times Fre \times Fre + 113 \times Cyc \times Fre - 30 \times NFo \times Fre
\]

\[
\Delta temp = 1.9 + 1 \times Cyc + 0.4 \times NFo + 0.5 \times Fre - 0.2 \times NFo \times NFo + 0.2 \times Cyc \times NFo + 0.3 \times Cyc \times Fre + 0.1 \times NFo \times Fre
\]

3.3. Interactions between process variables
The response contour plots in figure 8 illustrate the effects of the normal force \( NFo \) and of the number of cycles \( Cyc \), at high frequency \( Fre = 2.5 \) Hz. Graphical representations can help to explain the situation around the optimal point.

Figure 8. Response contour plots of average surface potential \( V_{AVG} \) (a), standard deviation of the surface potential \( \sigma_V \) (b) and temperature increase \( \Delta temp \) (c), at \( Fre = 2.5 \) Hz.

3.4. Genetic Algorithm-based optimization process
The Genetic Algorithm computation of the factor values that optimize the triboelectrification process necessitates 169 iterations. The predicted average value of the surface potential (-1633 V) is obtained for 10 sliding cycles, a normal force of 10 N, and a sliding frequency of 0.5 Hz. Five experiments were performed at these optimal values of the control factors (figure 9). The results were in good agreement with the genetic algorithm predictions.
Figure 9. Experimental result based on genetic algorithm optimal value; (a) Comparison of tribocharge results and GA prediction; (b) Surface potential mapping after tribocharging.

Figure 10. Material microscopic investigation pre (a) and post (b) tribocharging process.

These experimental conditions do not significantly change the aspect of the material surface. However, slight scratches appear on the surface (figure 10).

4. Conclusions
1) The number of friction cycles, the normal force at the surface of contact, and the relative sliding speed between the two bodies, are three of the major factors that affect the outcome of the triboelectrification process of polymers in dry conformal contact.
2) The association of response surface modelling with genetic algorithm techniques is an efficient way to optimize a triboelectrification process. The experimental results are in good agreement with the theoretical predictions.
3) Further experiments, with different polymer pairs of samples, will enable a better understanding of the physical mechanisms of triboelectrification.

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