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Effect of the Electric Discharge Confinemen on the Perforation Density of Porous Materials

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***Abstract*—Several methods to enhance the efficienc of paper electroperforation processes are presented in this work. In all the cases, the discharge confinemen effect is used for obtaining higher perforation densities than those found in the standard industrial processes. To quantify the efficienc of the proposed methods, statistical tools are used to characterize the 2-D perforation pattern.**

***Index Terms*—Electrostatic discharges, electrostatic perforation, needle-like electrodes, sparks.**

I. Introduction

ELECTROPERFORATION IS a widely used method in industry to generate tiny holes in thin porous material-like paper webs, packaging foils, biological membranes, etc. The main purpose of this technique is to enhance the air permeability of the porous material by means of a fast, reliable, and contactless method. Frequently, the material to be perforated circulates at a high speed in-between an array of needle-like electrodes. However, a major limitation of this technique is that there is a limit to the number of holes that can be created in a certain area due to the fact that the already generated holes offer an easier discharge path between the electrodes. Because of this self-limiting process, the porosity cannot be further increased beyond certain limit even if a longer exposure time or a higher discharge frequency is used. In this paper, it is shown that the effective distances between the perforations can be reduced by introducing a pierced matrix in-between the electrodes. This matrix is capable of limiting the lateral excursion of the electric discharge thus increasing the porosity of the material [1]. However, despite the benefits the introduction of elements between the electrodes in industrial environments presents serious drawbacks. In this regard, the other two proposed methods (modifie tips or unaligned setup) become more convenient.

II. Preliminary Physical Considerations

Since Meek and Loeb analyzed the complexity of the spark discharge process in 1940 [2]–[4], many other authors have significantl contributed to increase the understanding of the physical mechanisms involved in this phenomenon. However, the basic description introduced by Meek and Loeb has remained essentially unaltered [5], [6]. The spark discharge process fundamentally consists in the following sequence of events: first the formation of a precursor channel of ionized air between electrodes and, subsequently, the sudden triggering of an electron avalanche travelling from the cathode to the anode in a self-propagating streamer. This fl w of energetic electrons has practical applications, and in particular, it has been utilized to generate microperforations in thin porous materials such as paper, plastic, biological membranes [7], etc. Even though this work mainly focuses on the paper perforation process, the fina conclusions can be extended to other porous materials. According to the literature, the perforations occur as a consequence of local structural changes produced by the impact of sparks on the paper web [5], [8], [9]. The dimensions of the perforations may depend on several factors such as the type of web material (density, thickness, intrinsic porosity), spark energy, electrode geometry, etc., and are normally in the range of a few hundreds of micrometers. The separation between the electrodes plays a major role in the maximum perforation density that can be achieved [1]. This parameter also affects the spread of the perforations track over the running web. An obvious action to reduce the attractor effect [1] caused by the already made holes is to decrease the distance between the electrode tips. However, this is a critical parameter that in general cannot be reduced without putting at risk the integrity of the web material. In this regard, given the tight mechanical constraints for reliability considerations that are usually found in industrial facilities. This paper proposes two practical approaches to solve this problem:

- Use of a screening matrix to limit the excursion of the discharge path, in such a way that the sparks are forced to create new perforations.
- Modify the topology of the tips of the needles-like electrodes to confin the sparks and consequently increase the porosity of the material per unit area. In this case, there are two different solutions with similar effects (the utilization of shaped tips o unaligned setups).

III. Perforation Model for Running Webs

For the sake of simplicity, let us consider the opposed electrodes system illustrated in Fig. 1. It is also assumed that the discharge frequency is much higher than the ratio $v/\Delta s$, v, and

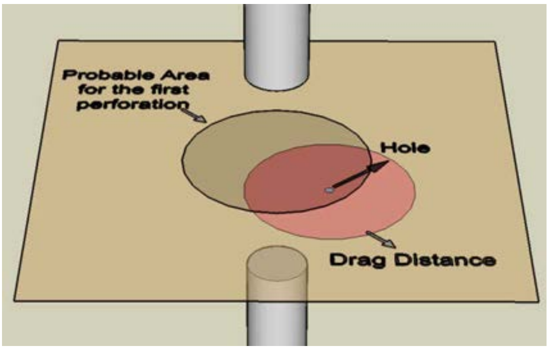

Fig. 1. Sketch showing the electrodes, the probable area of the firs perforation, the hole produced by the spark and the drag area.

Δs being the velocity of the web and the linear displacement of the paper during one discharge cycle, respectively.

The spark discharge process fundamentally consists in the following sequence of events: first the formation of a precursor channel of ionized air between electrodes and subsequently, the sudden triggering of an electron avalanche travelling from the cathode to the anode in a self-propagating streamer. This fl w of energetic electrons generates microperforations in thin porous materials such as paper, plastic, biological membranes [1]. The firs spark creates a hole in the paper randomly located inside a circular region centered on the electrode axis. The radius of this first-impac probable area strongly depends on the distance between the tips of the electrodes. It is experimentally observed that the impact area is reduced as the electrode separation decreases. Once the firs hole has been created, it becomes a boundary condition for the minimal impedance path between the electrodes so that, to generate a second hole, it is necessary to displace the perforated paper a certain distance away from the electrodes axis. The minimum distance needed to generate this second hole will be referred to as the drag distance. Evidently, the maximum porosity level achievable with the electroperforation technique is limited by the value of the drag distance parameter (a small drag distance corresponds to a larger number of perforations per unit length). Interestingly, the aforementioned attractor effect of a perforation over the spark discharge path can be exploited to reduce the drag distance without modifying the gap between the electrodes. The proposed solution consists in introducing a thin screening matrix between one electrode and the paper web with the objective of reducing both the reachable area by the firs discharge event and the drag distance for subsequent perforations.

IV. Experimental

The experimental setup consists in an array of two programmable step motors. The motors are fi ed in an optic table and move the sample with horizontal sweeps while between the tungsten electrodes occur the discharge.

The sparks are generated using the isolated gate bipolar transistors (IGBTs) based circuit shown in Fig. 2. It is basically a two-stage multiplier whose output is a train of pulses with a frequency controlled by the Vcontrol frequency and an amplitude of 1 kV (500 V $\times$ 2 stages) in the case of the circuit shown in Fig. 2. The amplitude of the output voltage can be incremented by changing the input voltage (500 V in Fig. 2) or including additional stages. Each stage is formed by two IGBTs in a half-bridge configuration The gate voltages are controlled using two optodrivers to sequence the charge of the 4.7 μF capacitor of the stage.

The output at the spark gap between the electrodes is a high voltage train of pulses with a wide frequency range (typically from a few Hz to 15 kHz). Fig. 2 shows the current oscillations in the output for a 1 kHz operating frequency.

The screening matrix considered in this study is a 2-D array of identical holes patterned on a ceramic substrate (many other alternative designs are shown in Fig. 3). Even though the required effect can be accomplished by using a matrix with a single hole, it is more convenient to have a 2-D array to facilitate the alignment of the experimental setup.

The screening matrix has two complementary effects. First, there is an effective reduction of the probable impact area for the firs discharge since the confinin effect caused by the hole in the matrix constitutes a new boundary condition. The second effect is to avoid that the already created holes in the paper become part of the minimal impedance path for the spark and therefore to ensure that subsequent sparks contribute to the creation of new holes.

The overall result is an increment in the number of perforations per unit of area. Since the matrix is in close contact with the discharge path and the hot electrodes, the substrate must be appropriately chosen for high temperature operating conditions. Due to such tight requirements, the Dupont 951 Green Tape (DGT) substrate has been utilized to fabricate the matrices. The process of synthesizing complex shapes using the DGT substrate is based on a multilayer approach, where the required design must be decomposed in separate layers. The holes have been drilled in the matrices using a Protolaser 200 LPKF machine.

The mechanization stage is followed by a standard lamination process. To bind the layers, a thermal cycle at a temperature of 100 °C and pressure of 300–500 psi for short times (3–5 min) is applied. Then, to finis the process of welding the constituent layers, the matrix should be cofire at 800 °C [10]. The ceramic matrix shown in Fig. 4 has been fabricated to illustrate the exposed concepts. The thickness of the matrix is 0.5 mm. The holes have a diameter of 0.3 mm, and the distance between first-neighbo holes is 2 mm. The matrix consists in an array of 5 $\times$ 5 holes centered in a 15.5 mm $\times$ 15.5 mm square area of the referred ceramic substrate.

As a proof-of-concept device, a simple two-electrode spark discharge setup was implemented. As the paper web, a 80 g.m^{-2} paper was used. The trials were performed at room temperature and in atmospheric conditions. The electrodes were tungsten needles. The separation between the tips of the electrodes was controlled using precision micropositioners. Fig. 5 shows the effect of inserting the screening matrix in the gap between the electrodes. To visually capture the discharge solid angle, the pictures were taken using long exposure times. Note that, in spite of the fact that the distances between the electrodes are the same in both pictures, the confinemen effect caused by the hole pierced through the ceramic substrate reduces the spread of the discharge paths (Fig. 5).

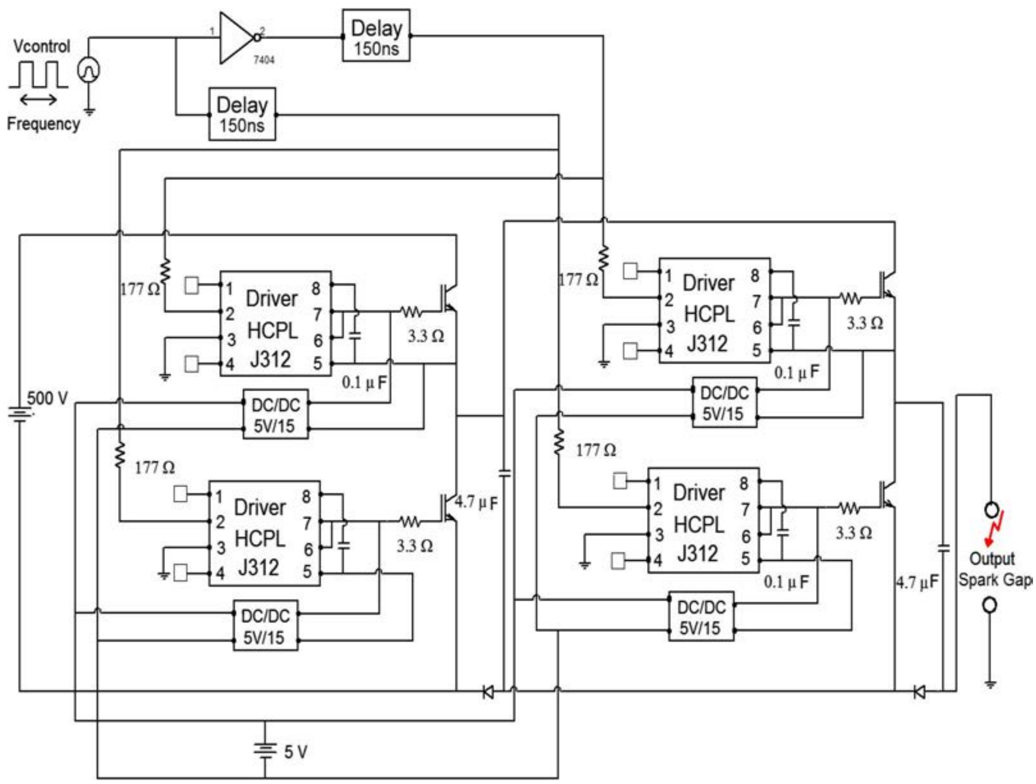

Fig. 2. Current profil at the electrodes during a 1 kHz spark train generation.

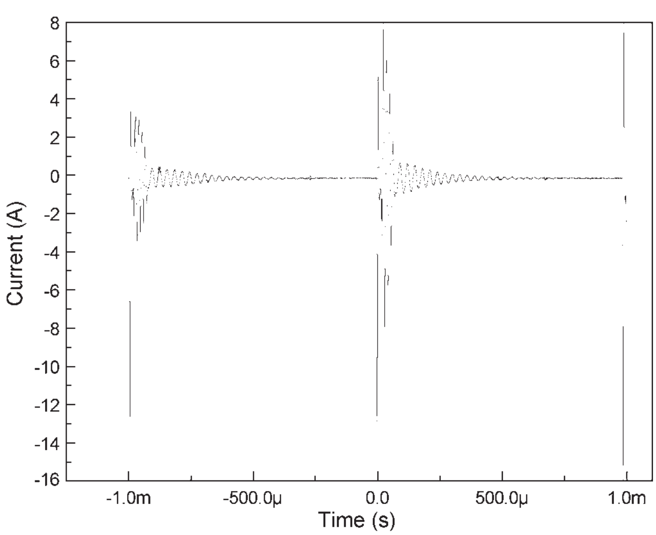

Fig. 3. Screening matrices implemented in Dupont 951 Green Tape substrates. The screening patterns are centered in a 15.5 mm × 15.5 mm square area.

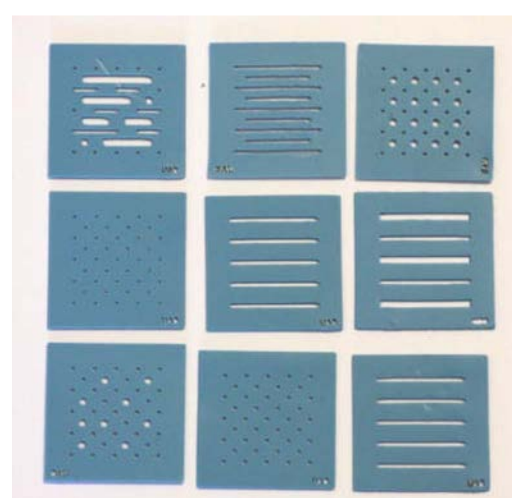

Fig. 4. Schematics of the two stages spark gap generator. The output voltage is 1 kV with frequencies controlled by the Vcontrol signal frequency.

The benefit of the screening matrices become evident in the 1-D perforation case from the drag distance evaluation [1]. However, a much more interesting case in industrial applications where a porosity enhancement is required is the 2-D distribution of the electrostatic perforations.

Fig. 6 shows a typical 2-D electroperforation pattern in a paper web. The analysis of the spatial distribution of the hole pattern shown in Fig. 7 requires the use of statistical tools such as the Spatstat package for R language [11].

As an example of the capabilities of this software package, Fig. 7(a) shows the empty space map, which reflect to some extent the drag distance phenomenon. The *distmap* function returns a pixel image whose pixel values are the empty space distances to the pattern measured from every pixel. The empty space distance is define as $d(u) = \min \|u - x_i\|$, the distance from a fi ed reference location u in the window to the nearest data point.

To deepen further into the consequences of Fig. 7 (upper), Fig. 7 (lower) shows the histogram for the nearest neighbor distances of the point pattern shown in Fig. 6. The minimum distance is 0.056 mm, whereas the median of the distribution

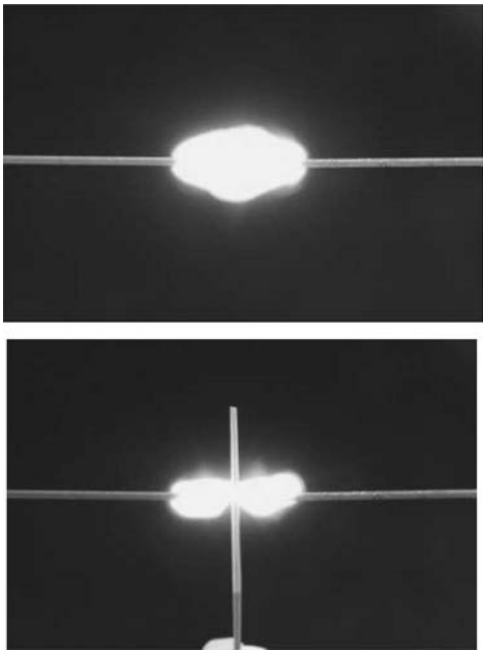

Fig. 5. Long exposure picture of a discharge sequence (upper) without matrix (lower) with matrix.

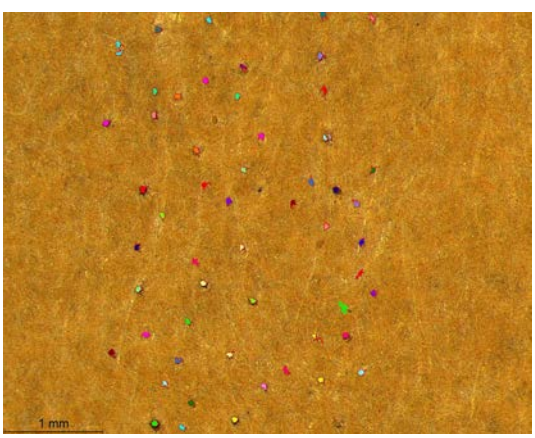

Fig. 6. Two-dimensional distribution of the electroperforated holes in a 50 m-thick paper web. The different colors identify the different sizes of the perforations.

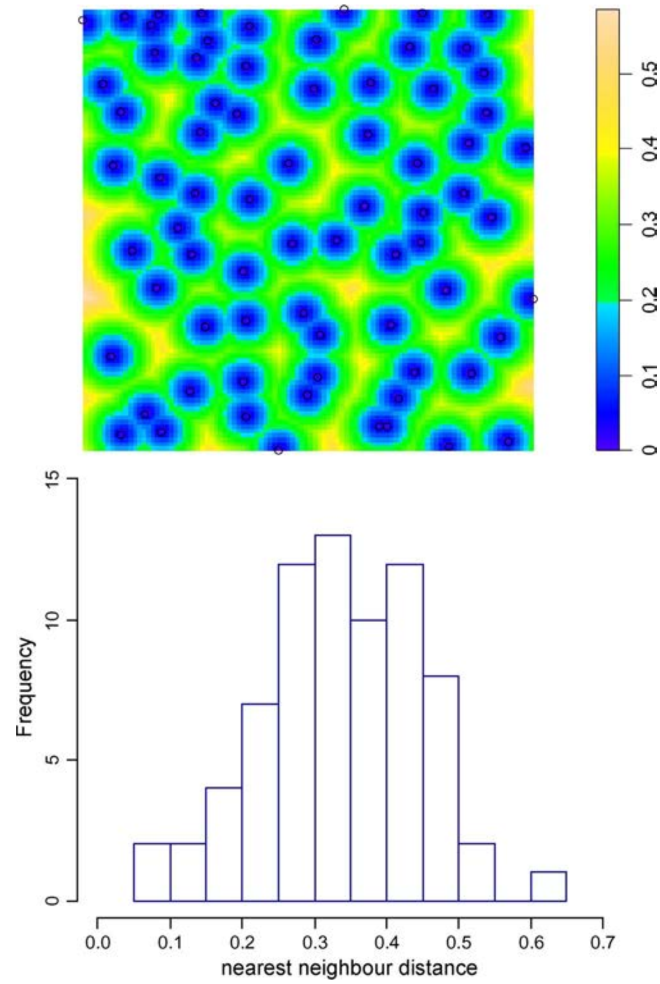

Fig. 7. (Upper) empty space map for the perforation distribution shown in the Fig. 6. (Lower) histogram of the nearest neighbor distances for the point pattern of Fig. 3.

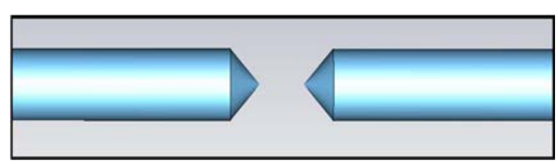

Fig. 8. Sharper needle-like electrodes.

is 0.33 mm. This demonstrates that the drag distance is not uniquely defined but actually there is a spread of the data.

The utilization of the screening matrices has shown their advantages in different ways for the 2-D perforation process. A reduction in the average dimensions of the perforations when the screening matrices are used becomes evident [9]. This is a consequence of the reduction of the drag distance when using screening which implies that a low number of sparks are collected by each hole.

A major disadvantage to this solution is that the introduction of a new element (the matrix) in an industrial system is not always welcome. This hampers their implementation in the industry because it is necessary to modify the existing facilities. Furthermore, the introduction of new elements may also have consequences for the reliability of the perforation setup.

V. Perforations With Sharper Needle-Like Electrodes

The utilization of sharpened tips (Fig. 8) produces similar effect regarding the confinemen of the spark discharge without the drawbacks of introducing additional elements in the setup.

The benefit of this method can be appreciated in Fig. 9, where the density of holes per unit area is drastically increased by the utilization of sharpened tips.

Typically, in an industrial electroperforation application, the minimal drag distance is limited to 0.26 mm, and the effect of sharpening the tips is a reduction of the average distance to 0.17 mm. These results are obtained using statistical tools like the cumulative distribution function (CDF) [11] for the nearest neighbors distance for samples obtained with and without sharp

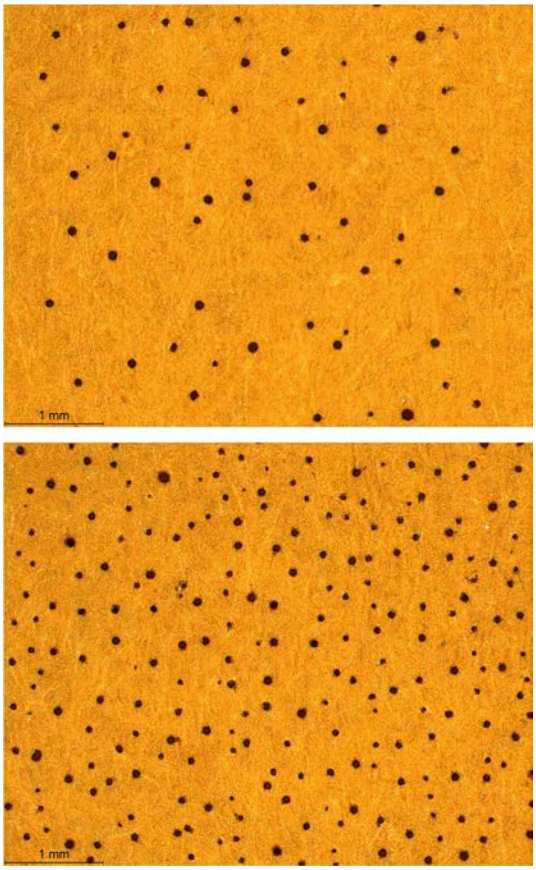

Fig. 9. Pattern perforation in paper (upper) with unsharped tips and (lower) with sharped tips

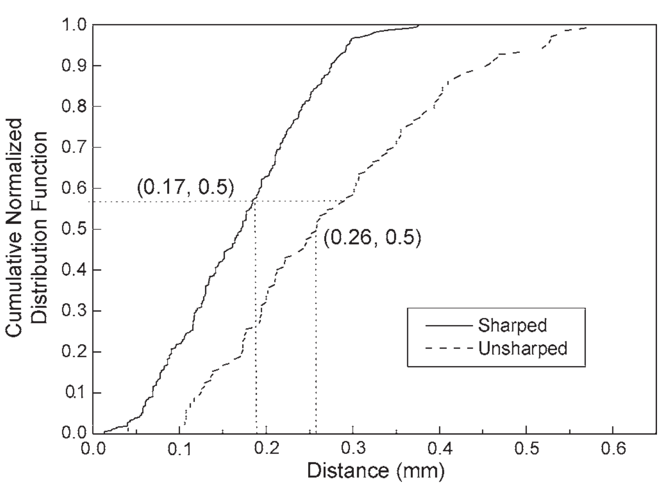

Fig. 10. Cumulative distribution function of distance to nearest neighbors.

electrodes (Fig. 10). With the CDF, it is possible to estimate the more frequent distances between nearest neighbor holes and to describe the probability distribution for each distance value. By means of this function, it is possible to quantify a 30% improvement in the drag distance when using the sharper tips.

Fig. 11 shows histograms for the distances between nearest neighbor holes in samples obtained with both types of tips.

The porosity is another important parameter in the industrial perforation processes of drilling thin membranes. In the fiel of

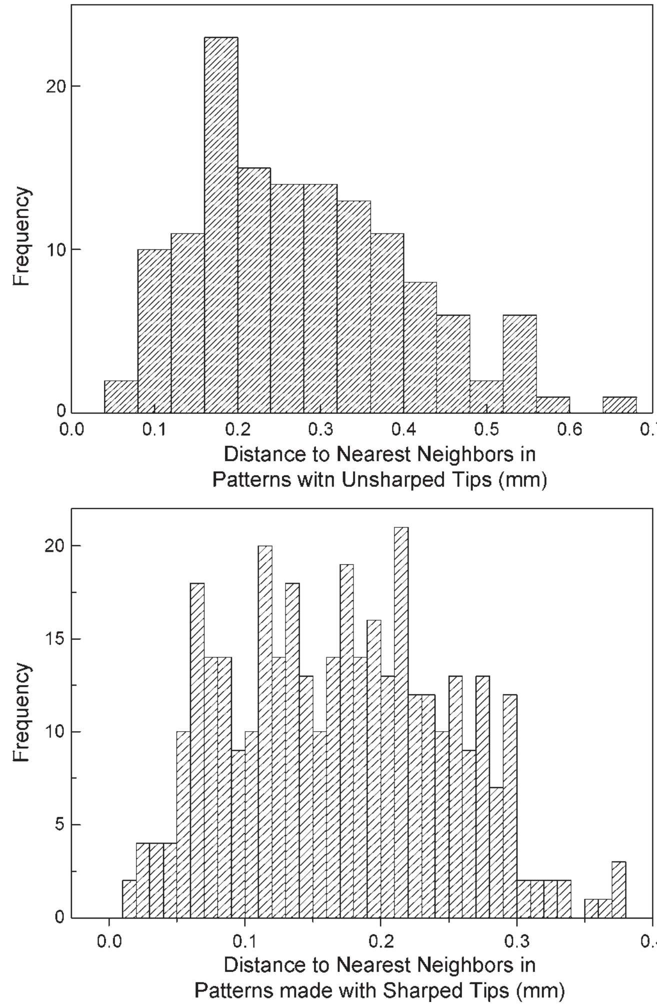

Fig. 11. Distances to nearest neighbors in patterns (upper) with unsharped tips (lower) and with sharped tips.

the electroperforated papers, a common unit to measure the air permeability is the Coresta. A coresta unit is a measurement of the volume of air passing in a given time through a test piece of paper of a given surface area under a specifie pressure difference. It is expressed in mL/min per cm at 1 kilopascal differential pressure differential.

For a typical industrial perforation system, the porosity value is around 310 coresta, and the holes generated have a mean size of 0.40 mm^2. By using sharper tips, it has been possible to achieve porosities up to 600 coresta with average values of 450 coresta. This represents an improvement of 45%. This value is obtained with mean size holes of 0.22 mm^2.

However, the continuous use of the electrodes causes a tip degradation which becomes more severe in the case of sharper tips, resulting in a reduction of performance of the industrial setup.

Unaligned tips offer similar results as that of sharper tips in the porosity of paper perforation pattern because the mean in this parameter is 460 coresta. Therefore, the unaligned tips can be considered as an alternative method to take advantage of the tip effect, but without the drawback of a fast tip degradation. However, the development of this topic is in progress.

VI. Conclusion

The drag distance has been identifie as the fundamental parameter that limits the density of perforations in paper webs and therefore the maximum porosity level that the electroperforation technique is able to produce.

The experimental results shown in this work point out that the use of a screening matrix and sharper needle-like electrodes can enhance the perforation density. These methods are better suited for situations in which practical or mechanical constraints in the perforation system do not allow to bring the electrodes closer. Work is in process to apply the described techniques to industrial production.

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