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Porosity enhancement by the utilization of screening patterns in electro-perforated paper webs

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In this work, a technique to enhance the porosity of electro-perforated paper webs using screening matrices is described. The proposed approach relies on the confining effect that acts on a train of sparks when forced to pass through a small hole pierced through a ceramic substrate located in-between two needle-like electrodes. It is shown how the maximum porosity level achievable by the electro-perfora-tion process depends on the drag distance parameter. Since the proposed method is aimed at reducing the latter, an eventual enhancement of the number of perforations per unit area can be obtained. The method has been experimentally tested. It is worth mentioning the suitability of the matrix-aided paper perforation process for its use in industrial environments.

1. Introduction

Since Meek and Loeb analyzed the complexity of the spark discharge process in 1940 [1 3], many other authors have signifi cantly 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 [4,5]. The spark discharge process fundamentally consists in the following sequence of events: first, the formation of a precursor channel of ionized air between the electrodes and subsequently, the sudden triggering of an electron avalanche travelling from the cathode to the anode in a self propagating streamer. This flow 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 [6], etc. Even though this paper mainly focuses on the paper perforation process, the final conclusions can be extended to other porous materials. In a typical configuration, the web material runs between an array of opposite needle like electrodes, which continuously generate perforations by means of spark discharges. According to the literature, the perforations occur as a consequence of local structural changes produced by the impact of sparks on the paper web [4,7,8]. The dimensions of the perforations may depend on several factors such as the type of paper (density, thickness), spark energy, electrode geometry, etc., and are normally in the range of a few hundreds of microns. The main problem with this perforation 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 created holes provide an easier discharge path between the elec trodes. As a consequence of this self limiting process, even using a longer exposure time by means of reducing the web velocity or increasing the discharge frequency, the porosity cannot be further increased. Additionally, the separation between the electrodes plays a major role in the maximum perforation density that can be achieved. This parameter also affects the spread of the perforations track over the running web. An obvious action to reduce the attractor effect is to decrease the distance between the electrode tips. However, this is a critical parameter that cannot be diminished beyond a certain limit without raising the risk of causing irrepa rable damage to the passing material. Given the tight mechanical constraints that can be usually found in industrial facilities, this paper is aimed at providing to some extent, a practical solution to this problem. To this end, the 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 is proposed.

2. The model

For the sake of simplicity, let us consider the single electrodes system depicted in Fig. 1. It is also assumed that the discharge frequency is much higher than the ratio $v/\Delta s$, v and Δs being the velocity of the web and the displacement of the paper during one

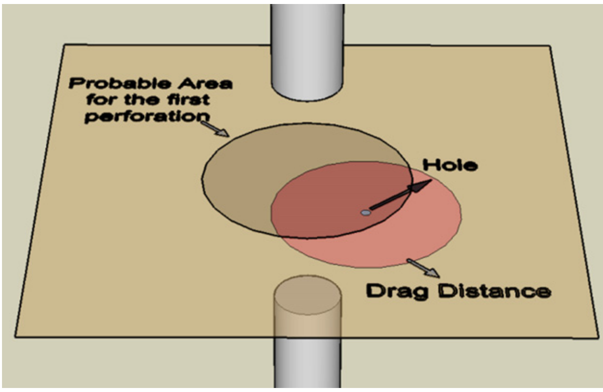


Fig. 1. Sketch showing the electrodes, the probable area of the first perforation, the hole produced by the spark and the drag area.

discharge cycle, respectively. The first spark creates a hole in the paper randomly located inside a circular region centered on the electrode axis. The radius of this first impact probable area is strongly ruled by 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 first hole has been created, it becomes a boundary condition for the minimal impedance path between electrodes so that, in order to generate a second hole, it is necessary to displace the perforation a certain distance away from the electrodes axis. The minimum distance needed to generate this second hole is defined 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).

Notably, the aforementioned attractor effect of a perforation over the spark discharge path can be exploited to design a method 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 first discharge and the drag distance for subsequent perforations.

3. The screening matrix

The screening matrix considered in this study is a 2D array of holes patterned on a ceramic substrate (see Fig. 2). Even though the required effect can be accomplished by using a matrix with a single hole, it is more convenient to have a 2D array in order 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 first discharge since the confining 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 with the creation of new holes. The overall result is an enhancement of 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 should be appropriate for high temperature operating conditions. Due to such special 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 matrices holes have been drilled 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 finish the process of welding the constituent layers, the matrix must be co fired at 800 °C. For additional details see reference [9]. The ceramic matrix shown in Fig. 2 has been fabricated

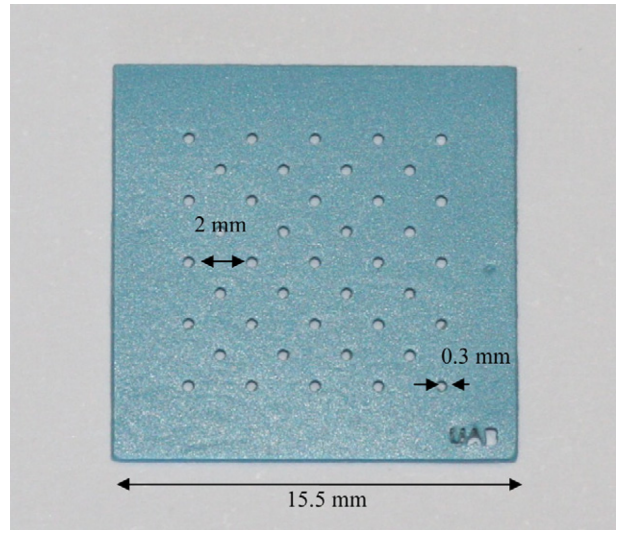


Fig. 2. Screening matrix implemented in a Dupont 951 Green Tape substrate. The holes have a diameter of 0.3 mm and the distance between the neighbor holes is 2 mm. The matrix consists in an array of 5 × 5 holes centered in a 15.5 × 15.5 mm square area.

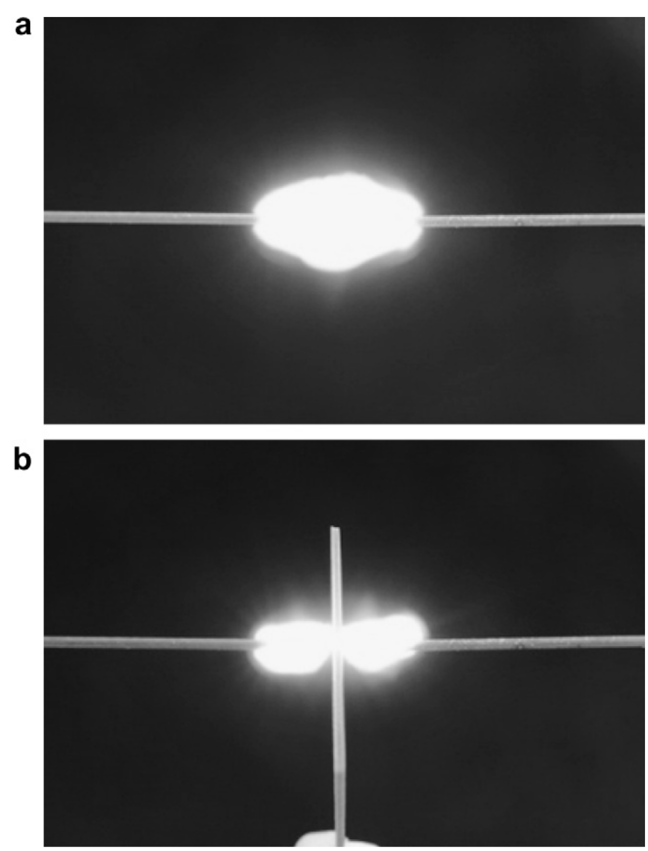


Fig. 3. Long exposure picture of a discharge sequence (a) without matrix (b) with matrix.

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 neighbor holes is 2 mm. The matrix consists in an array of 5 × 5 holes centered in a 15.5 mm × 15.5 mm square area of the referred ceramic substrate.

4. Experimental setup and measurements

With the purpose of experimentally demonstrate the usefulness of the concepts introduced in the previous Sections, a simple two electrode spark discharge setup was implemented. As the paper web, a 80 g m^{-2} paper was used. The experiments 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 micropositioners. Fig. 3 shows the effect of inserting the screening matrix in the gap between the electrodes. In order to visually capture the discharge solid angle, the pictures were taken using a long exposure time. Note that, in spite of the fact that the distances between the electrodes are the same in both pictures, the confining effect caused by the hole pierced through the ceramic substrate reduced the spreading of the discharge paths (Fig. 3b). Fig. 4 shows typical distances between perforations that can be obtained without (left picture column) and with (right picture column) including the screening matrix as a function of the distance between the electrodes. The average values were calculated using several pictures (not shown here) for each situation. It was observed that the separation between the perforations increases with the separation between the electrodes, what reflects the increase in the dispersion of the discharge trajectories. A larger density of holes when using the screening matrix was also evident. The linear distribution of holes shown in Fig. 4 was the result of a sufficiently slow displacement of the web paper between the electrodes (first column) and between the ceramic matrix and one of the electrodes (second column). A low velocity of the web was required to ensure that many sparks were attracted by each hole before a new perforation was generated. Under these conditions, the drag distance can be estimated by averaging the distances between consecutive perforations. These average values are plotted in Fig. 5.a. As can be observed, the utilization of the ceramic matrices yields a clear drag distance reduction beyond the data standard deviation. It is worth mentioning, at this point, that the data standard deviation largely depends on the experimental conditions. The perforation density can be estimated as the inverse of a circular area with a drag distance diameter. Fig. 5.b shows a clear

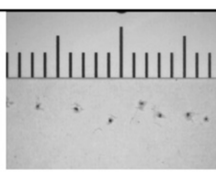
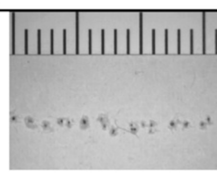
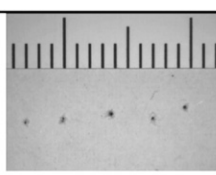
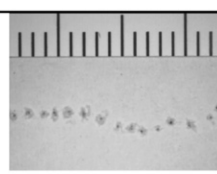
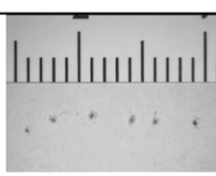
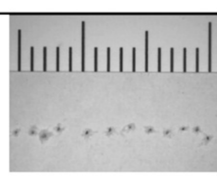
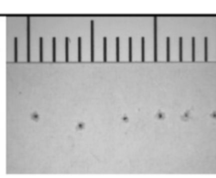
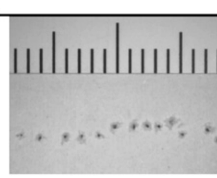
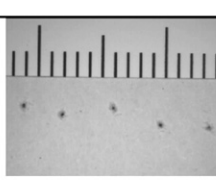
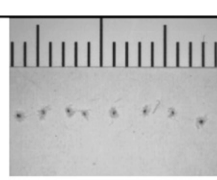
Electrode separation	Drag Distance without Screening Matrix	Drag Distance with Screening Matrix
5 mm		
5.5 mm		
6 mm		
6.5 mm		
7mm		

Fig. 4. Table with the perforation pattern generated by the spark for different electrode distances without and with the ceramic matrix.

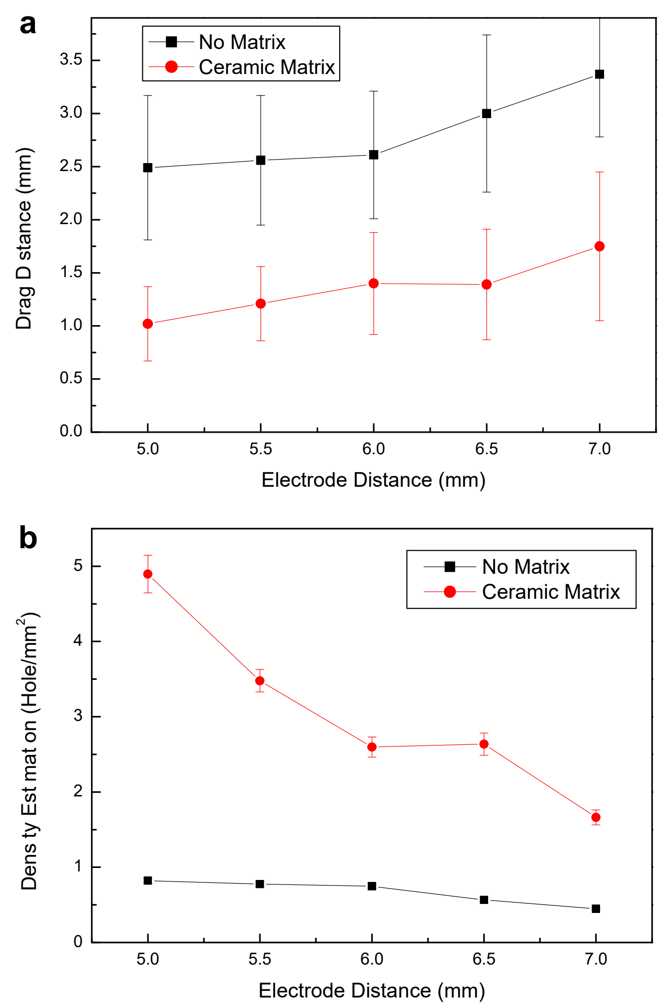


Fig. 5. Effect of the ceramic matrix in the drag distance. a) Drag distance versus electrode separation with and without the confinement effect. b) Estimated perforation density with and without a matrix.

increment in the perforation density when the matrix method is used (Fig. 5).

5. Conclusions

It has been demonstrated that the utilization of a screening matrix introduces a tighter boundary condition for the discharge process, which leads to a reduction of the spatial dispersion of the sparks. The drag distance has been identified 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 showed in this work point out that the use of a screening matrix can enhance the perforation density. The method is best suited for situations in which practical or mechanical constraints in the perforation system do not allow to bring the electrodes closer.

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