Effect of the electric discharge confinement on the perforation density of porous materials

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Abstract—A method to enhance the perforation density of porous materials by means of electrical discharges is reported. The method consists in using screening matrices to confine the discharges so as to reduce their lateral excursion.

Keywords - electrostatic discharges, sparks, needle-like electrodes, electrostatic perforation.

I. INTRODUCTION

Electroperforation is a widely used method in industry to generate tiny holes in thin porous materials 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 limits even if a longer exposure time or a higher discharge frequency is used. In this work, it is shown that the 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.

II. PRELIMINARY PHYSICAL CONSIDERATIONS

Since Meek and Loeb analyzed the complexity of the spark discharge process in 1940 [1-3], many other authors have significantly 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 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 work mainly focuses on the paper perforation process, the final 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 [4,7,8]. 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 microns. 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 in general cannot be reduced without putting at risk the integrity of the running web. In this regard, given the tight mechanical constraints for reliability considerations that are usually found in industrial facilities, this paper proposes a practical solution to this problem. The proposed method consists in using a screening matrix to limit the excursion of the discharge path, in such a way that the sparks are forced to create new perforations.

III. PERFORATION MODEL FOR RUNNING WEBs

For the sake of simplicity, let us consider the opposite electrodes system illustrated in Fig. 1. It is also assumed that the discharge frequency is much higher than the ratio \( \frac{v}{\Delta s} \), \( v \) \( \) and \( \Delta s \) being the velocity of the web and the displacement of the paper during one 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 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 first hole has been created, it becomes a boundary condition for the minimal impedance path between the electrodes so that, in order 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 first discharge event and the drag distance for subsequent perforations.

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

Figure 2. Screening matrices implemented in Dupont 951 Green Tape substrates. The screening patterns are centered in a 15.5 mm X 15.5 mm square area.

IV. EXPERIMENTAL

The screening matrix considered in this study is a 2D-array of identical holes patterned on a ceramic substrate (many other alternative designs are illustrated in 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 must be appropriately chosen for high temperature operating conditions. Due to such 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. After the mechanization stage a standard lamination process comes. 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 should be co-fired at 800°C. For additional details see reference [9]. The ceramic matrix shown in figure 2 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-neighbor holes is 2 mm. The matrix consists in an array of 5X5 holes centered in a 15.5 mm X 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.m² 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. Figure 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 long exposure times. Note that, in spite of the fact that the distances between the electrodes are the same in both pictures, the confinement effect caused by the hole pierced through the ceramic substrate reduces the spread of the discharge paths (figure 3.b). The benefits of the screening matrices become evident in the one-dimensional perforation case from the drag distance evaluation [10]. However, a much more interesting case in industrial applications where a porosity enhancement is required, is the two-dimensional distribution of the electrostatic perforations.
Figure 3. Long exposure picture of a discharge sequence (a) without matrix (b) with matrix.

Figure 4 shows a typical 2D electroperforation pattern in a paper web. The analysis of the spatial distribution of the hole pattern shown in figure 4 requires the utilization of sophisticated statistical tools such as the Spatstat package for R language [11].

Figure 4: 2D distribution of the electroperforated holes in a 50 μm-thick paper web. The different colors identify the different sizes of the perforations.

As an example of the capabilities of this software package, Fig. 5.a shows the empty space map, which reflects in some extend 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 defined as \( d(u) = \min_i \|u-x_i\| \), the distance from a fixed reference location \( u \) in the window to the nearest data point.

To deepen further into the consequences of Fig. 5.a, Fig. 5.b shows the histogram of the nearest neighbour distances for the point pattern of Fig. 4. The minimum distance is 0.056 mm, whereas the median of the distribution is 0.33 mm. This demonstrates that the drag distance is not uniquely defined but actually there is a spread of the data.

Figure 5: (a) empty space map for the perforation distribution showed in the figure 4. (b) histogram of the nearest neighbour distances for the point pattern of Fig. 4

The utilization of the screening matrices has shown their advantages in different ways for the 2D perforation process. Some of this advantages are difficult to quantize such as the effect in the perforation area, without the proper measure setup. Nevertheless, a reduction in the average dimensions of the perforations when the screening matrices are used becomes evident. This is a consequence of the reduction of the drag distance when using screening which implies that minor number of sparks are collected by each hole.

V. CONCLUSION

It has been shown that the utilization of a screening matrix introduces a 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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REFERENCES


