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A method to detect mechanical cracks creation and/or propagation in insulators

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Abstract- Fracto-emission is the ejection of electrons and positive ions from mater subjected to a mechanical fracture. The mechanical fracture is accompanied by the creation and/or the propagation of cracks in the mater, leading to a succession of fracto-emissions. First, we have described, through analytical equations, the amount of surface charge produced by a mechanical fracture and how it can be measured with an external measuring circuit. Then, this measuring device is used to detect the appearance of cracks and their propagation under mechanical stress. This method allows to study the electro-mechanical interactions, particularly for insulators for which the electromechanical breakdown model is being considered.

I. INTRODUCTION

Over the past few years, power electronics, which uses semiconductor devices, has made it possible to transform and adapt electrical energy with less volume and greater efficiency than conventional systems. This has been possible due to advances in both power semiconductor devices and packaging of modules where these semiconductors are integrated. The dielectric breakdown of solid insulators used as substrate is one of the primary causes of power electronics module failure. Ceramics (AlN , Al_2O_3 , BeO) in the high-power domain and composites (epoxy glass) in lower power domains are suitable candidates to be used as a power module substrates. The dielectric breakdown mechanism of these insulators has been described as an electro-mechanical breakdown model, by considering that both electrical and mechanical properties are strongly linked. Hence, the detection of the crack creation and propagation in these solid insulators under the electrical and/or mechanical stress, may pave the way to a better understanding of their dielectric breakdown mechanism.

The electro-mechanical breakdown model was inspired by the Griffith Criterion on crack propagation in brittle materials [1]. In this electromechanical model, it is proposed that the mechanical failure is driven by the electric-field-assisted propagation of the crack to fully understand the interaction of the mechanical and electrical phenomena involved, we propose to first analyze and quantify the electrical phenomena induced solely by the mechanical crack as it propagates.

Griffith claims that the condition for a crack to propagate is the reduction of potential energy caused by the creation of a new open surface [2]. A simple method to propagate of a crack through the material can be accomplished using a 3-Point Bending (3PB).

Our study assumes that the dielectric material has a pre-existing micro-crack that can be propagated when sufficient load is applied under the 3PB. There are three main phases, according

to the time that the load is applied as shown in Figure 1, t_1 , when no load is applied. Then at t_2 , the crack has been propagated using the 3PB, causing the mater in the dielectric to separate. At t_3 , the dielectric is mechanically ruptured. The mater separation, releases pressure waves, intercepted as Acoustic Emissions (AE). In parallel, during the same occurrence of mater separation, due to the existence of charges in the dielectric, the bonds are broken and charge separation takes place, as shown in Figure 2 .

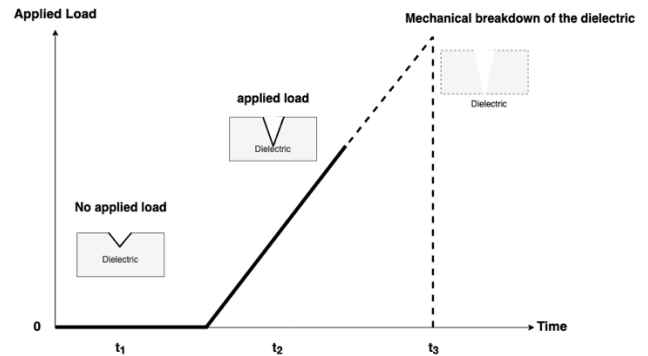


Figure 1 Crack propagation in a pristine dielectric with a pre-existing micro-crack under 3PB loading.

The instant appearance of charges during and following a fracture in the dielectric material is called Fracto-Emission (FE), a phenomena first mentioned by J.T. Dickinson [3] while observing Electron Emissions (EE) and Positive Ion Emission (PIE) during the fracture of graphite, epoxy and later, on the FE in fiber-reinforced and particulate filled composite [4], [5]. He also studied the role of charge separation during the FE of alumina filled epoxy and SiO_2 [6]. His research on FE [7] led the way of the study of this phenomena on ceramics and brittle material [8]–[10]. Dickinson et al. [11] studied both FE and AE, confirming that FE are generally accompanied by AE during the crack propagation. With both phenomena occurring simultaneously, a new electrical method is proposed in the following to detect all electrical phenomena induced with the creation and propagation of a crack, due to FE, influencing the surface charges density of the dielectric insulator.

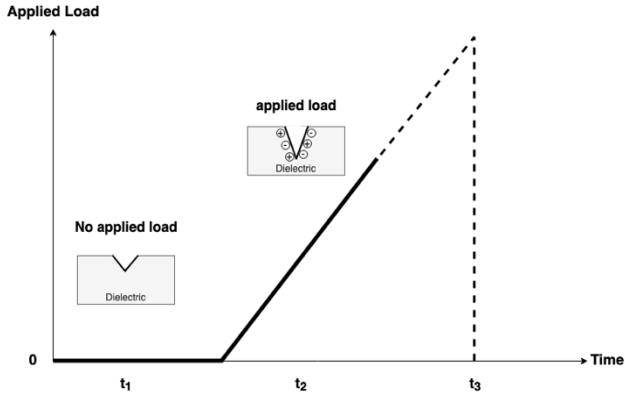


Figure 2 Dielectric with its charges before and after crack propagation under 3PB load.

First of all, we have fixed the following assumptions:

- the sample structure is homogeneous;
- the sample thickness is sufficiently thin compared to the surface to use a unidimensional formulation;
- the edge effects are neglected.

The relationship between the surface charges density at electrodes A and B and the internal charges, is given by equation 1:

$$\sigma_A = -\sigma_B = \frac{\epsilon_0 \epsilon_r V_0}{d} \quad (1)$$

The expression of V_0 , i.e.: the equivalent voltage to apply to the sample in order to eliminate the charge densities, has to be defined to understand the parameters that takes part in the expression of the surface charge density. Using the expression of electrical displacement $D(x)$, which combines the electrical field $E(x)$ and the polarization $P(x)$, followed by the integral of the electric field over the sample's thickness and the Poisson's equation, the following result is obtained:

$$V_0 = -\frac{1}{\epsilon_0 \epsilon_r} \left(d \int_0^d \rho(x) dx - \int_0^d x \rho(x) dx \right) + \frac{1}{\epsilon_0 \epsilon_r} \int_0^d P(x) dx \quad (2)$$

Further simplifications, using the total charge Q and the average depth of charge penetration $\langle x \rangle$, introduced in [12] with the substitution of it in (2), will provide the expression of the charge density σ_A as :

$$\sigma_A = -\frac{d-\langle x \rangle}{d} \cdot \frac{Q}{S} + \frac{1}{d} \int_0^d P(x) dx \quad (3)$$

where $\langle x \rangle = \frac{\int_0^d x \rho(x) dx}{\int_0^d \rho(x) dx}$ and $Q = S \int_0^d |\rho(x)| dx$.

For further simplification, we suppose that on all the plan involving x abscise, the permanent polarization is either 0 or

uniform, resulting to no equivalent charges. This hypothesis will give the new expression of σ_A :

$$\sigma_A = -\frac{d-\langle x \rangle}{d} \cdot \frac{Q}{S} \quad (4)$$

II. Sample and Experimental Method

A. Sample

Since this method of detection is an electrical one, the dielectric sample must undergo a metallization one both sides as shown in Figure 3.

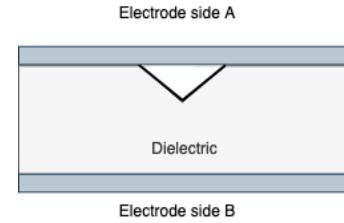


Figure 3 Dielectric sample with metallization on both sides

B. Experimental setup

With the electrodes placed on each side of the insulator, using a fast detection circuit, when the surface charge density evolves by the means of a 3PB, a current pass through the circuit, which is recorded by a fast oscilloscope. The schematic of the setup is given by Figure 4.

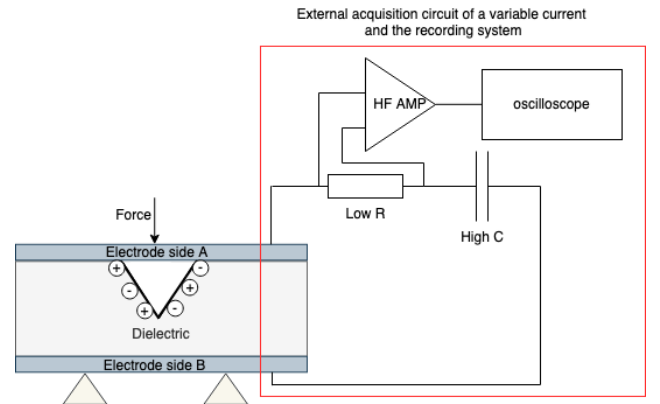


Figure 4 Schematic of the measuring circuit.

Indeed, under the application of the 3PB, a crack (or cracks) will be propagated and create fracto-emission. Therefore, the surface charge density is no longer null due to $\rho(x) \neq 0$, $\langle x \rangle \neq 0$ and $Q \neq 0$ observed in

Figure 5-(1). While the created and/or propagated crack produce the charges resulted by the fracto-emission, these charges can recombine:

Figure 5-(2-4). With the variation of the volume charge density, $\langle x \rangle$ and Q varies too, leading to a surface charges variation. In Figure 5, the difference scenarios of the charge density variation have been shown.

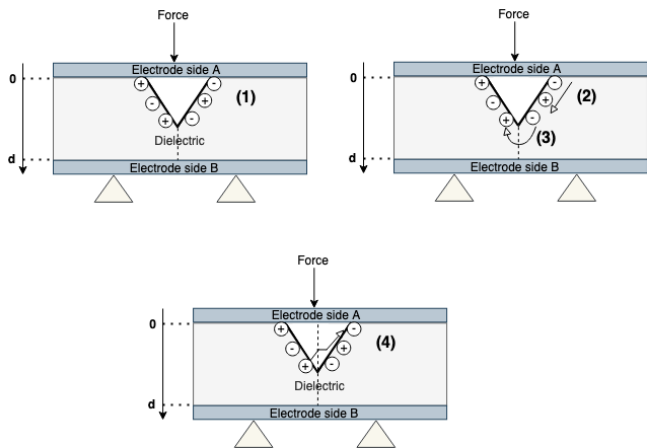


Figure 5 Different scenarios leading to a surface charge density variation.

In Figure 5-(2) refers to the charge recombination on the crack surface, while (3) is the recombination in volume and (4) across crack (i.e.: partial discharges). All these phenomena may be fast, so that both measuring and recording devices must have a wide bandgap.

III. Results and Discussion

In this study 1 mm-thick epoxy-glass laminated substrates (PCB-FR4), (length: 60 mm, width: 30 mm), have been used as shown in Figure 6. The copper metallization was 365 μm -thick (top side surface: 5mm \times 30mm, full metallization on bottom side). The sample underwent the 3PB employing the setup displayed in Figure 7.

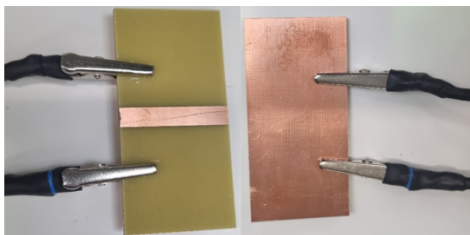


Figure 6 Epoxy sample to be tested: top and bottom sides.

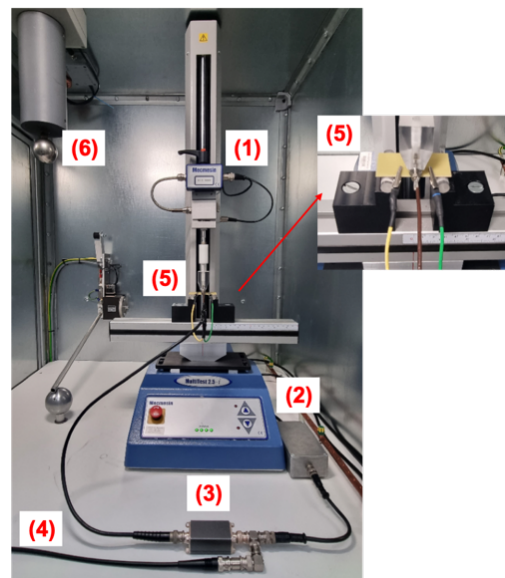


Figure 7 Experimental setup. (1): 3point bending machine, (2) amplifier power supply, (3) HF amplifier, (4) wire between the amplifier output and the oscilloscope, (5) Epoxy sample. (6) AC 50Hz high voltage output.

It has to be considered that the same acquisition can be done under high voltage, or after the application of a high voltage (electrical pre-stress), to observe the effect of the electrical field on the crack creation and/or propagation. However, this would not be discussed in this paper. A typical signal recorded during a 3PB test is shown in Figure 8. The force was applied up to the mechanical failure of the whole epoxy sample. Numerous signals such as the one of Figure 8 may be recorded during the mechanical force application, betraying a fracto-emission activity linked to crack creation and propagation.

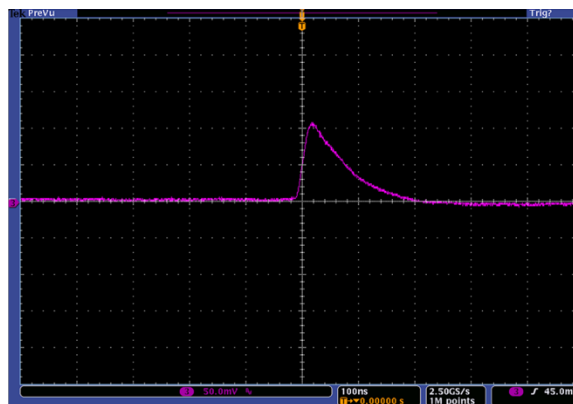


Figure 8: Typical signal recorded during a 3PB test (epoxy sample)

The signal/noise ratio is sufficiently high to consider that the recorded signal is a useful signal and not noise or artifact, since it is correlated with the acoustic emissions heard during the crack(s) propagation.

IV. Conclusion

This new method of crack creation and/or propagation detection, establishes the relationship between the FE and an external induced current. The signal can be detected and recorded. This new tool will play an important role in the understanding of the dielectric breakdown mechanism of insulators where both electrical and mechanical properties are strongly linked. The next step of this novel method would be to use it to observe the influence of the electrical field on the propagation of existing micro-cracks in the dielectric material, bringing further light to the electromechanical dielectric breakdown mechanism and its model.

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REFERENCES

- [1] « VI. The phenomena of rupture and flow in solids », *Philos. Trans. R. Soc. Lond. Ser. Contain. Pap. Math. Phys. Character*, vol. 221, n° 582-593, p. 163-198, janv. 1921, doi: 10.1098/rsta.1921.0006.
- [2] A. T. Zehnder, « Griffith Theory of Fracture », in *Encyclopedia of Tribology*, Q. J. Wang et Y.-W. Chung, Éd., Boston, MA: Springer US, 2013, p. 1570-1573. doi: 10.1007/978-0-387-92897-5_259.
- [3] « The emission of electrons and positive ions from fracture of materials ».
- [4] J. Dickinson, A. Jahan-Latibari, et L. Jensen, « Fracto-emission from fiber-reinforced and particulate filled composites », *Mol. Character. Compos. Interfaces*, p. 111-131, 1985.
- [5] J. Summerscales, *Non-destructive testing of fibre-reinforced plastics composites*, vol. 2. Springer Science & Business Media, 1990.
- [6] J. T. Dickinson, L. C. Jensen, et A. Jahan-Latibari, « Fracto-emission: The role of charge separation », *J. Vac. Sci. Technol. Vac. Surf. Films*, vol. 2, n° 2, p. 1112-1116, avr. 1984, doi: 10.1116/1.572682.
- [7] J. Dickinson, L. Jensen, S. Lee, L. Scudiero, et S. Langford, « Fracto-emission and electrical transients due to interfacial failure », *J. Adhes. Sci. Technol.*, vol. 8, n° 11, p. 1285-1309, 1994.
- [8] Y. Enomoto et M. M. Chaudhri, « Fracto-emission during Fracture of Engineering Ceramics », *J. Am. Ceram. Soc.*, vol. 76, n° 10, p. 2583-2587, oct. 1993, doi: 10.1111/j.1151-2916.1993.tb03984.x.
- [9] N. S. Brar et Z. Rosenberg, « On the possibility of fracto-emission in ceramics during shock compression », in *AIP Conference Proceedings*, Colorado Springs, Colorado (USA): AIP, 1994, p. 1759-1762. doi: 10.1063/1.46169.
- [10] B. Lawn, « Fracture of brittle solids », *Camb. Solid State Sci. Ser.*, p. 194, 1993.
- [11] J. T. Dickinson, A. Jahan-Latibari, et L. C. Jensen, « Electron emission and acoustic emission from the fracture of graphite/epoxy composites », *J. Mater. Sci.*, vol. 20, n° 1, p. 229-236, janv. 1985, doi: 10.1007/BF00555916.
- [12] G. Dreyfus et J. Lewiner, « Electric Fields and Currents due to Excess Charges and Dipoles in Insulators », *Phys. Rev. B*, vol. 8, n° 6, p. 3032-3036, sept. 1973, doi: 10.1103/PhysRevB.8.3032.