TRACKING RESISTANCE OF VARIOUS MATERIALS IN VACUUM

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Abstract: Many vacuum instruments used in industry and scientific research apply high voltage components. Vacuum performs as an insulator with theoretically infinite breakdown voltage. Surface of dielectrics between two electrodes inside a vacuum chamber is the weakest link for a possible electrical breakdown (tracking). This paper focuses on examination of a vacuum pressure influence to the surface breakdown voltage of a various materials. Results were compared and led to determination of an appropriate materials for a design of internal connectors in electron microscopes produced by the company Thermo Fisher Scientific.

Keywords: high-voltage, breakdown, tracking, dielectric, glass, Kapton, alumina, PVDF, PEEK

1 INTRODUCTION

Because of a lack of any particles that could conduct electric current, vacuum is usually considered as a perfect insulator with both an infinite resistance and breakdown voltage. Real vacuum is just a clean and dry gas environment with a very low pressure. Anyway, a low current running between two electrodes placed in a vacuum chamber is mostly caused by a finite resistance of dielectrics and a field electron emission between the electrodes [1]. When cathode and anode are separated by an insulator, a triple junction of the vacuum, metal, and dielectric is place with highest probability of electron emission. The emitted electrons are accelerated and when they incidence with the dielectric, it can heat up its surface, and lead to deformation of an electric field, a secondary emission, and a drop of the surface resistance. This is the most likely the cause of a tracking in vacuum, when a voltage exceeds a certain level [2].

Usually to compare and categorize various insulating materials from the perspective of tracking resistance, a standardized comparative tracking index (CTI) tests are done. CTI in material datasheets represents the minimum voltage, that causes a tracking when specific amount of an electrolyte is applied on the insulator surface [3]. With respect to other ambient conditions as humidity and level of contamination, the CTI is often used for estimation of a proper creepage distance. However, the CTI tests cannot be done in a vacuum, and as consequence, many high voltage designs for vacuum instruments are based on empirical estimations or simulations.

The main goal of this work was to create a simple method to measure the surface breakdown voltage in a vacuum, below a point of a minimum at Paschen's curve, which describes the dependency of the breakdown voltage in gas on the product of pressure and distance of electrodes. The point is specific for each type of gas. In the air, a minimum breakdown voltage $U_{b\ min}$ is 352 V, when $(p \cdot d)_{min}$ is 73,3 Pa·cm [1]. If the distance between cathode and anode is fixed, in the pressure above this point U_b slowly rises. But, below this point, U_b rapidly rises. Our experiments showed that the breakdown voltage rises while decreasing pressure, but not as much as it was expected according to the Pashen's law. It is assumed that an interaction between the dielectric surface and the gas influenced this shift. A few perspective materials were characterised when submitted to pressures from

4 mPa up to 50 Pa. Measurements were done in a vacuum chamber that allowed high voltage experiments.

2 DESIGN OF MEASUREMENT METHOD

The first step in establishing a suitable method was a design of a proper electrode system. Planar electrodes were chosen to be used on the top of a specimen surface. There were two options how to create them. A photographic process similar to a PCB manufacturing was one of the options. The second option was to stick metal tape stripes on the specimen. Although the photographic process seemed to be more accurate, it would be also more complicated and time consuming. Besides, an anisotropic etching would have to be used to avoid an overhanging. Final decision was to use the copper tape strips, which is simple, cheap, and flexible solution. The strips were cut by a template whose dimensions are shown in **Figure 1**. The distance between the electrodes (4 mm) is the same as in the CTI tests. Width and rounding of edges were chosen to comply requirements for a homogeneity of electrostatic field in the middle of specimen.

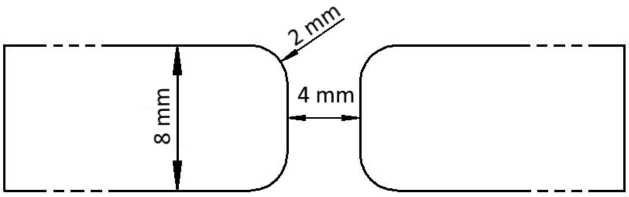

Figure 1: Dimensions and electrode layout.

The second step was verification that the field between electrodes was homogenous. To do that, the electrostatic field was simulated using a simulation software CST Studio [5]. The results of the simulation can be seen in **Figure 2**. The cathode and an enclosure borders were set to zero potential, and the anode to 1200 V potential. By simple calculation it was proved, that the electric field intensity between electrodes, which are 4 mm apart, should be 300 V/mm. Important was that lines between electrodes were parallel, matching a theoretical value of the intensity, and not exceeding a double of this value at the rounded edges.

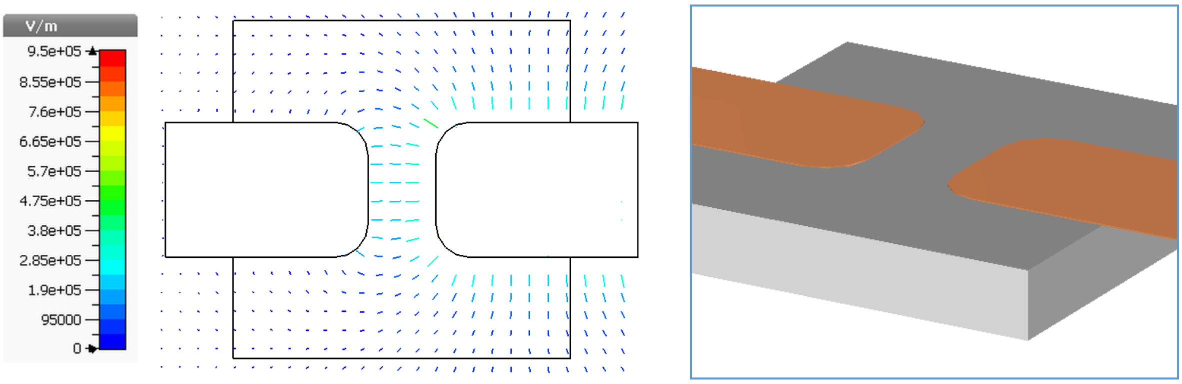

Figure 2: Simulation of electrostatic field and 3D representation of an electrode model

Then, the Paschen's curve for 4 mm distance of electrodes was calculated and plotted. To do this, the equation:

$$U_b = \frac{B \cdot p \cdot d}{\ln(p \cdot d) + a} \tag{1}$$

was used, where B = 480.22 [V·Pa^{-1}·m^{-1}] and a = 1.31 [-] are constants established from the Paschen's minimum point for the air [4].

Figure 3 shows Paschen's curve that was calculated on theoretical basis. In the chart, top border of 50 Pa for measurements was estimated. Due to the vacuum chamber and properties of a turbo pump, experimental measurements of the tracking could be done in the pressures form 4 mPa up to 50 Pa.

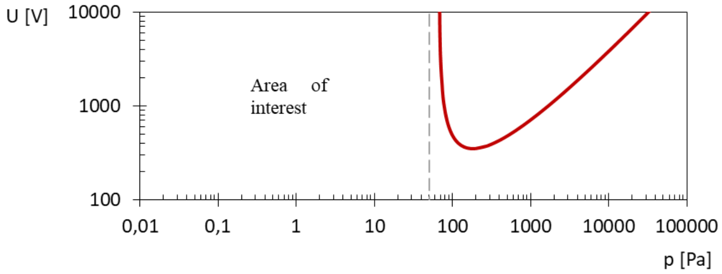

Figure 3: Paschen's curve for the air and a 4 mm distance of electrodes.

3 DESCRIPTION OF MEASUREMENTS

3.1 INSTRUMENTS AND SETUP

The vacuum chamber consisted of a glass cap and a steel bottom, which was connected to a zero potential. The glass cap was surrounded by a Faraday cage. A two vacuum pumps Edwards XDS-10 and EXT 255H together with a needle valve Pfeiffer EVN 116 and a vacuum gauge Edwards WRG-SL were used to achieve required pressures. A HT 55-I was used as a source of high voltage. Limitation for continuous electric current was set to 25 µA. An output of the current sensor was connected to an input of an Agilent 54641D osciloscope. Usually, horizontal scale was set to 200 ms/d and vertical scale to 5 V/d.

Figure 4: Picture of the used instruments and the specimen in chamber.

3.2 MEASUREMENT PROCEDURE

A four-millimetre wide template was used to stick the copper tape strips on specimens. One of the strips was also stuck to the steel bottom of chamber, while the other one was connected by a wire, through a ceramic bushing, to negative output of the source. The area between and around of the electrodes on the specimen was cleaned by an isopropyl alcohol. The specimen was then placed on a PMMA underlay. The chamber was then closed and vacuum pumps were turned on. After pressure in the chamber stabilized at a certain value, voltage started to rise till tracking appeared. Tracking usually lead to electric current pulse with a peak higher than 150 µA, or series of pulses that were less than 100 ms apart. At this point, the high voltage source was turned off, and the voltage was recorded.

Measurements were done on specimens of a Sylamit 1000 PVDF, Ketron 1000 PEEK, Kapton HN tape, IS-400 (glass-reinforced epoxy laminate) with and without a solder mask, Alumina, and glass. Because IS-400 was available with and without the solder mask, influence of this parameter to the tracking was also observed.

3.3 RESULTS

Despite that every point in the charts below represents an average of five measured values for the particular pressure, deviations of values were still quite high, especially in low pressure. This was the reason why no trend line was used in charts. However, within the range where breakdown voltage rises (pressure between 5 and 20 Pa) a power function would mostly fit with reliability (R^2) more than 0,98. At the pressure of 50 Pa a purple light above cathode was observed, which was considered as side effect of ionization of the air and formation of plasma cloud. Concurrently, raise of the electric current was with the increasing voltage rather smooth, which indicates that electric current went rather through the air, then on the surface of dielectrics.

Among organic materials that were investigated, best resistance to tracking was found in case of the PVDF, which had almost 10 kV breakdown voltage in pressure 5 Pa, and about 14 kV in lower pressure as 0.5 Pa. In the range between 5 to 20 Pa a dependency of the breakdown voltage on the pressure can be in case of PVDF described by the following function: $U_B = 165{,}02 \cdot p^{-1{,}833}$ [kV], ($R^2 = 0{,}9882$).

As it is shown in the **Figure 5**, the solder mask on IS-400 had almost no influence to tracking properties in lower pressures, but in pressures 0,5 to2 Pa the breakdown voltage is at about 1,5 kV higher, so the improvement is quite visible.

Because the glass and Alumina are inorganic materials, their characteristics were plotted in the separated chart. It can be seen that Alumina has better tracking properties in low pressure and it can withstand about 2 kV more than a glass. On the other hand, glass has shown a slightly higher tracking resistance in the pressure above 5 Pa. The breakdown voltage dependency on the pressure for these two materials in the pressures from 5 to 20 Pa can be also mathematically described by a power function with quite high reliability, as in the case of organic materials.

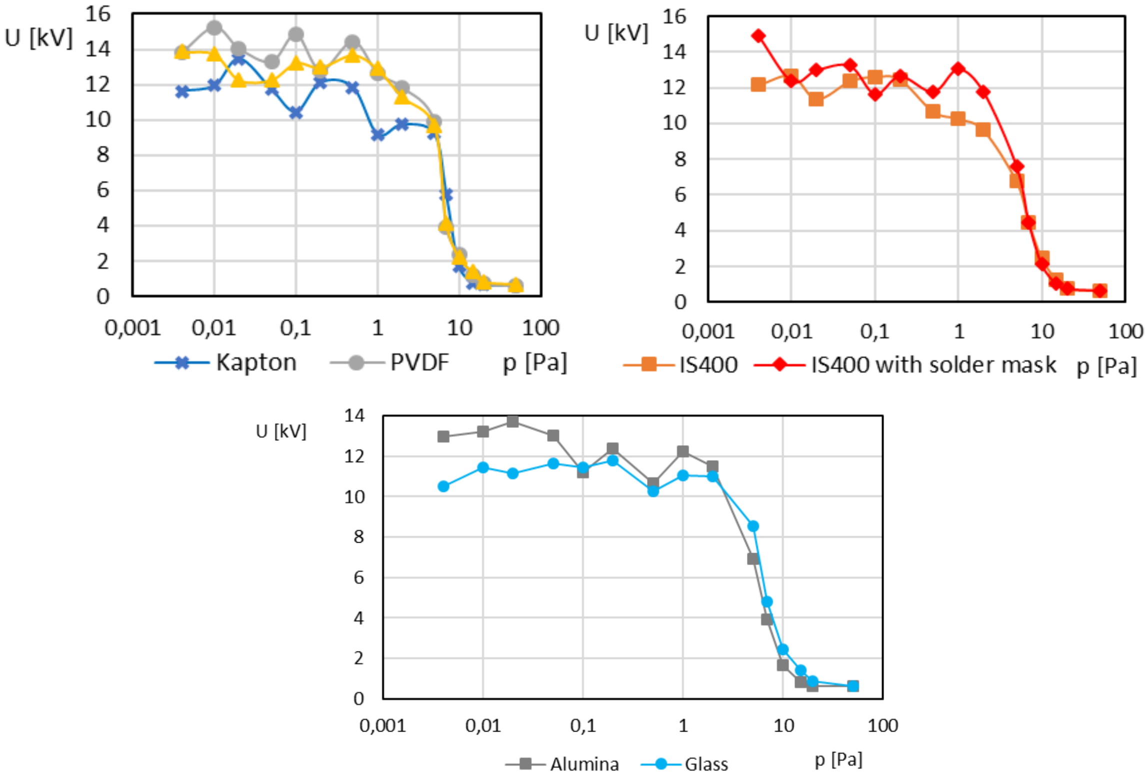

Figure 5: Breakdown voltage dependencies on pressure for Kapton, PVDF, PEEK, IS400, IS400 with solder mask, Al_2O_3, and glass. The solid lines are guides to the eyes.

4 SUMMARY

The topic of this paper deals with a little explored field of tracking in a vacuum. Important is a discovery that area, where breakdown voltage strongly depends on the pressure, was found at lower pressures than estimations based on the Paschen's curve would expect. In our case, it was mostly between 1 and 20 Pa for electrodes that were 4 mm apart. This indicates that some interaction between surface and gas must play an important role in tracking. Also, interesting fact is that all investigated materials showed a similar behaviour in the studied pressure range and their dependency of breakdown voltage could be described by power functions. This means that further investigation should focus on other parameters as distance and shape of electrodes or surface finishing, rather than variety of dielectrics. We concluded that further improvements on the experimental setup such as scheme to allow testing more than one sample at a time at certain pressure in the vacuum chamber could help gather statistical data more quickly.

This characterisation of materials is also useful for prototyping and design of new high voltage components that works suitably under vacuum conditions. From this point of view, it is important to know at what distance, voltage and pressure, the components can operate. Results shown in this paper were already used by Thermo Fisher Scientific to determinate requirements for a clearance distance of a data connector on the ceramic substrate, that is just a few millimetres away from part with voltage of 10 kV, while surrounded by a vacuum of few millipascals. Another example is PVDF separator that is used to increase a creepage distance in components that are used in an electron microscope.

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