Inkjet printing: a new technique for manufacturing solid insulation systems

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***Abstract*- This work investigates several dielectric coatings, of different thicknesses, applied over metalized layers. More precisely, acrylate-based dielectric materials were fabricated using two different additive manufacturing techniques: spin-coating and inkjet. While microscope imaging showed that uniform layers could be achieved by both techniques, breakdown strength, along with partial discharge measurements showed that microstructural defects were present in the bulk and that the quality of the printed layers decreases as the thickness of the layers increases. Nevertheless, it is shown that lacquer insulating layers, of variable thickness, can be easily obtained by inkjet printing. Even without any process optimization, they exhibit good dielectric properties, which shown their potential for electrical engineering applications.**

I. INTRODUCTION

Additive manufacturing, along with inkjet printing are new, versatile technologies for industrial manufacturing. Initially reserved for the field of PCB production, they are finding their place in other domains as well, from the food [1] to the bio-medical industry [2]. Digital manufacturing technologies, along with Industry 4.0 process follow-up, allow for an exponential production growth, sustained by fast developing industrial solutions. For example, the field of inkjet printing of microelectronics has seen a growing demand in the last years since, compared to the conventional fabrication techniques, inkjet printing significantly reduces the number of process steps, the energy consumption or the generated waste [3].

These new manufacturing techniques are extremely versatile, allowing, the development of innovative geometries, which would unlikely be achievable with conventional fabrication technologies Take, for example, the case of a field grading terminations. Nowadays, stator bar terminations are fabricated using semi-conductive tape that overlaps with the high-voltage and the conductive parts. Using classic manufacturing techniques, the field grading could be achieved only by variating the number of semi-conductive layers, as their thickness could not be changed during the process. In the same context, an additive manufacturing technique could allow for a finer control of the electric field distribution, as the thickness of all the layers could be controlled on the go and insulating or conductive layers, or paths, could be printed exactly where needed, for example, using a pattern available in a CAD file, generated by an FEM design optimization.

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Fig. 1. Inkjet printing head (real product and working principle, from [4])

Since both 3D printing or inkjet are usually depositing “drops on demand” (Figure 1), thus extremely small volumes of material each time, both technologies are usually associated with small or thin structures. Thus, a major challenge is finding the right materials for achieving micrometric layers while also developing a printing technology that allows fabricating larger components, adapted for higher voltage applications. This is not a simple task because not only that each thin layer has to respect the rigor of higher voltage operation, but the complete insulation system (ensemble of dielectric, conductive, maybe semi-conductive materials) has to be highly performing. By working with the right materials and the optimal process allowing them to be easily printed together, an important technological milestone could be reached. Moreover, with the contribution of the Industry 4.0 manufacturing process control, fully automated production lines could be put together. Using arrays of sensors for integrated quality control measurements after each printing step, an 100% controlled process could be established, allowing for early diagnosis in case of defects and close to 0% rejection rate.

In this context, this work presents a material screening study conducted while researching an 100% UV lacquer for an inkjet HV coating application. Coating materials screening are common and adhesion or stability tests (also known as “85/85 tests”) are used to evaluate the quality of the layers and their compatibility with other materials, such as conductive, metallic layers. When it comes to thicker, multilayer coatings or to multi-material systems, the previous tests can point towards the weaker point of the assembly but do not characterize the overall volume of the coating, especially for thicker layers. As the quality of thicker layers could be sometimes hard to assess, one possible solution comes from the use of dielectric tests such as breakdown measurements or partial discharge measurements. The results of electrical tests are even more significant when the printed insulating layer will be used for electrical applications, over energized nodes.

II. Sample Preparation and Preliminary Results

Drop on demand processes, like 3D additive manufacturing or inkjet, use either pressure-regulated ink dispensers or piezo-printheads, such as those depicted in Figure 1, to create droplets with the desired size and pattern recurrence. As the name suggests it, small ink volumes, of only a few pL, are being ejected through printing nozzles, on demand, using piezoelectric actuators. By activating a specific number of nozzles and with the control of the excitation voltage, the width, length and thickness of the printed layers could be easily controlled. Consequently, printing a dielectric coating with inkjet needs a certain amount of work to build an ink system capable of printing the liquid, selecting an appropriate printhead and tuning the printing parameters. Depending on the physical properties of the ink, mainly density, viscosity and viscoelasticity, this process can take up to 2 weeks and, for some fluids, might be impossible.

To allow the screening of a large number of different inks and blends between inks, we have used the spin coating technique as an alternative, as it is an easy and fast way to manufacture the thin layers needed for the electric characterization tests. Spin-coating allows the creation of layers in the range between less than 1 µm up to 50-100 µm. The layer thickness depends mainly on the viscosity of the ink and the spinning speed. The final printed layer is uniform and thus ideal for our study. Meanwhile, a major drawback of spin-coating is having a large amount of wasted ink during the process. Spin-coating is not suitable for a final industrial process but for a small number of samples, this is not an issue.

In the first part of the study, the behavior of several low viscosity UV lacquers, of acrylate type without volatile organic compounds, provided by Lott-Lacke GmbH, Germany, was investigated. Like similar products existing on the market, these acrylate-based inkjet inks contain low-molecular weight photosensitive molecules, along with low-molecular weight monomers and oligomers. Unlike UV inks used in the packaging industry, this ink doesn't contain pigments. During the polymerization process, both monomers and photo-initiators react while being exposed to a specific UV dose (mJ/cm^2). As explained in [5], the UV curing process is a radiation curing process in which a solid film is obtained from a wet film, through crosslinking and polymerization. Although this process is similar to thermal polymerization, the UV curing doesn't require high temperatures, as photo-polymerization can be initiated at room temperature. Furthermore, the process is extremely fast and the polymerization occurs in less than a second.

For this work, a Polos spin150i spin-coater was used for creating dielectric layers of 7 µm, over a mirror polished stainless-steel disc substrate. The weight of the ink was measured using a PCE LSZ220 S/N:168 laboratory scale. In order to achieve the right thickness, the dependency of the layer thickness with respect to the spinning speed and the viscosity of the material, was studied, as shown in Figure 2. Figure 3 shows the power law connecting the spinning speed and the viscosity of the ink (material 6 was excluded).

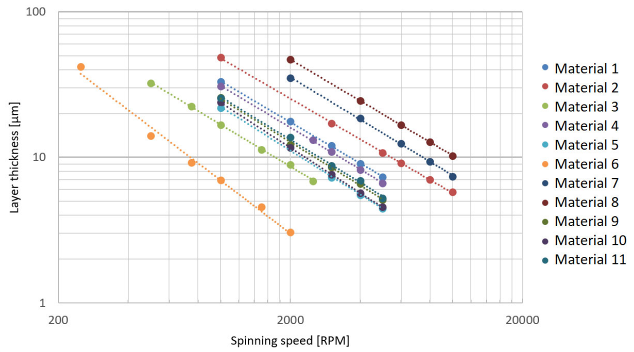

Fig. 2. Layer thickness vs. spinning speed

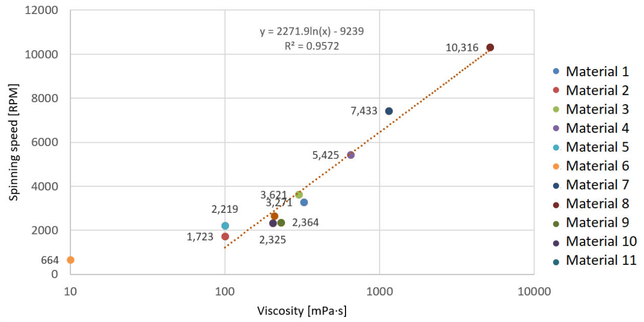

Fig. 3. Spinning speed for 10µm layer vs. viscosity

The same single-layered samples were tested electrically, using dielectric breakdown strength measurements (Figure 4). This testing technique was found to be a reliable tool for evaluating the defect-free characteristics of a dielectric printed over conductive, metallic layers or substrates.

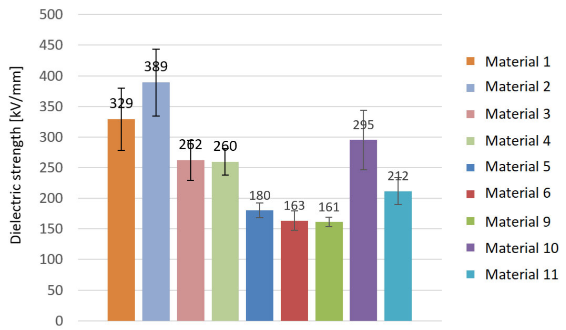

Fig. 4. Dielectric strength of 10µm films, measured directly on dielectric

VDE electrodes were used for applying the high voltage potential in contact with the dielectric and a DC voltage ramp of 50 V/s was applied, for less than 20 s, according to the IEC 60243-1 and IEC 60243-2 standards. 5 samples from each material were tested in air, under normal conditions. Based on the results presented in Figure 4, material n°2 had the highest breakdown strength and was selected for the second part of the study, in which the manufacturing process was switched from spin-coating to inkjet. Material 1, the second viable candidate, was not further investigated due to its high dissipation factor, as shown in Figure 5. The dissipation factor measurements were performed with a Hioki IM3570 Impedance analyzer and an Agilent 16451B standardized dielectric test cell.

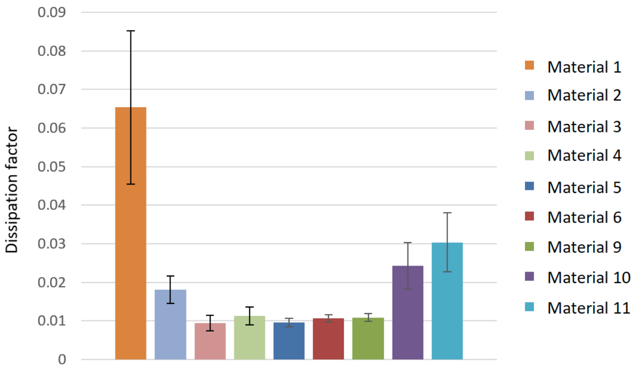

Fig. 5. Dielectric losses of 10µm films, measured directly on dielectric

An important part of the follow-up study – inkjet printing of the same materials (not presented here) – allowed us to perform the transition between these two different printed technologies. First, using drop watching technology, we were able to find the best recipe for printing uniformly spread dielectric layers (with a 60 mm diameter) sandwiched between silver electrodes (with a 50 mm diameter), starting with a stainless steel, mirror polished substrate. After optimizing the UV curing process, we were able reproduce as good as possible the samples manufactured by spin-coating at the beginning of the study. Yet, one drawback was quickly discovered: it was impossible to obtain the same thickness for and individual layer printed by inkjet as it was previously the case for spin-coating. Actually, in order to obtain homogeneous layers, without dewetting, layers three times as thick had to be printed! This change in thickness has also strongly affected the overall quality of the samples from an electrical point of view (see Figure 6).

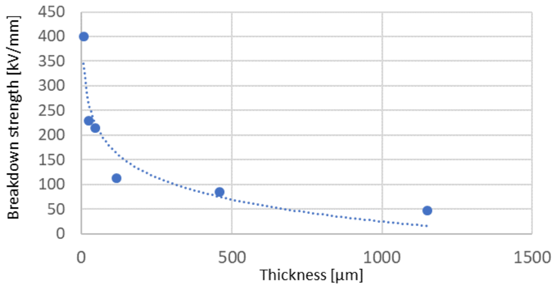

Fig. 6. Breakdown strength values obtained for various layer thicknesses

The increase in the number of defects with the thickness of the investigated material is a well-known phenomenon in dielectric studies and it was, unfortunately, confirmed by our results, as shown in the previous figure. Based on these results, a compromise was found between a thin layer that is subject to dewetting and a thicker, uniform layer, having a higher number of defects. Hence, the final thickness for the inkjet-printed dielectric (23 µm) was selected. Also, the structural uniformity of the sample was maintained, as shown by the SEM microscopy image (see Figure 7).

A number of 42 samples, with 20 dielectric layers, intercalated with 20 conductive layers, were produced and tested in the second part of the study. Their characteristics are presented and discussed in the following section.

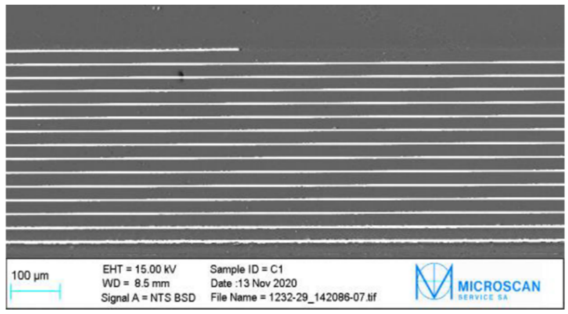

Fig. 7. SEM microscopy presenting several inkjet-printed dielectric layers "sandwiched" between inkjet-printed silver inter-layers

III. Electrical Properties of "Thick" Samples: Results and Discussion

A. *Electrical capacitance: measurements and results*

One important advantage of additive manufacturing comes from its compatibility with Industry 4.0 non-destructive quality control techniques. For the printed dielectric layers, it was decided that the capacitance measurements would be one viable technique, as it fast and reliable. The capacitance values were obtained using a Hioki IM3570 Impedance analyzer, equipped with an Agilent 16451B standardized dielectric test cell. The plotted values (Figure 8) were measured at 10 kHz.

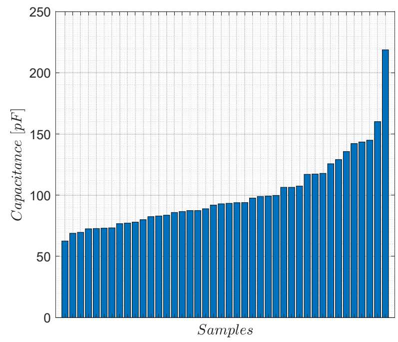

Fig. 8. Capacitance of the investigated samples, in ascending order

As shown in Figure 8, an unexpected variance in capacitance was found. As the number of layers cannot be doubted and as the tolerance in the thickness of the dielectric cannot explain such differences, the only plausible explanation is that a certain number of layers were short-circuited, which leads to having fewer dielectric layers in parallel and, thus a higher overall capacitance. One can suppose that the reason for the short circuit is related to the characteristics of the printed intercalated electrodes. This assumption is based in the fact that during preliminary dielectric tests that were carried out in air (not presented here), the breakdowns systematically took place on the edges of the top printed electrode (Figure 9, right), which implies a weakness in this point. Furthermore, some SEM images have shown that there was a significant bulge of the electrode towards the edge (Figure 9, left). This bulge is a known phenomenon in inkjet printing and, it is explained, in particular, by shrinkage phenomena during the curing process.

Consequently, if the bulge of the electrode towards the edge is large enough, two successive layers of electrodes could be electrically in contact, forcing the corresponding capacitive elements to be short-circuited.

Another important consequence is that, when the breakdown strength will be investigated later, it will be important to know the number of dielectric layers that are actually exposed to the electric stress. These capacitance values also allowed us to determine the number electrically separated layers. Surprisingly, a large dispersion in the number of layers was found, ranging from 20, the expected value, to only 6. An average permittivity of $\varepsilon_r \approx 3.2$, was also extracted from the capacitance values.

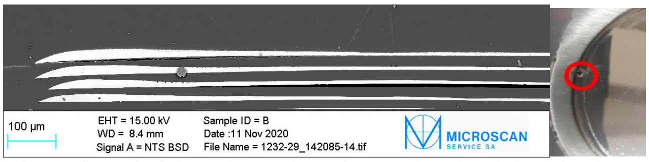

Fig. 9. Electrode deformation as shown by SEM imaging (left) and an inset with a picture of a tested sample, emphasizing the breakdown site (right)

B. AC and DC dielectric breakdown strength results

The AC breakdown strength of 33 samples out of the 42 analyzed previously was measured in oil, in a plane-plane configuration (imposed by the upper printed electrode and by the stainless-steel bottom substrate), according to the IEC 60243-1 and IEC 60243-2 standards. A 0.5 kV_{rms}/s (50 Hz) voltage ramp was applied until breakdown (< 20 s). For 14 out of 33 samples, the irreversible destruction occurred on the edge of the electrode (42%) as for 19 samples out of 33, the breakdown occurred in the center of the sample (58%). 5 samples were tested in oil, under DC voltage, and 75% of them presented a breakdown on the edge of the electrode and only 25% in the center of the upper electrode. The location of the breakdown as a function of the number of layers is represented in Figure 10. One interesting observation is that the modules having the lowest number of layers tend to exhibit a breakdown on the edge.

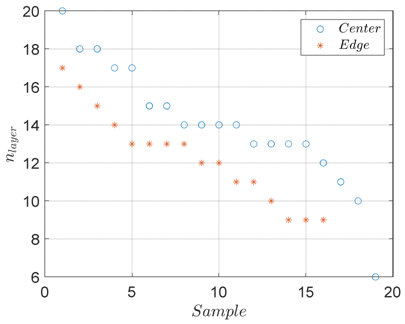

Fig. 10. Point of dielectric breakdown according to the number of layers

Based on the dielectric breakdown values under AC and DC voltages, obtained for some of the samples (Figure 11), we can also observe that none of the AC breakdown strength values are superior to 14 kV/mm (arithmetic average value 6.9 kV/mm) whereas the values of the DC dielectric strengths vary between 47 and 53 kV/mm. The high difference between AC and DC breakdown strengths led us to perform additional DC testing, on samples that were not initially included in the study.10 additional samples were tested under a DC ramp and an average DC breakdown field of 47 kV/mm was found, confirming the previously obtained results. Thus, the ratio between the average DC and AC disruptive field (the peak value will be used) can be calculated as follows:

$$\frac{E_{d\,mean\,DC}}{E_{d\,mean\,AC}} = \frac{48.1}{\sqrt{2}\cdot 6.9} = 12.95 \qquad (1)$$

This ratio is quite important and two explanations are possible.

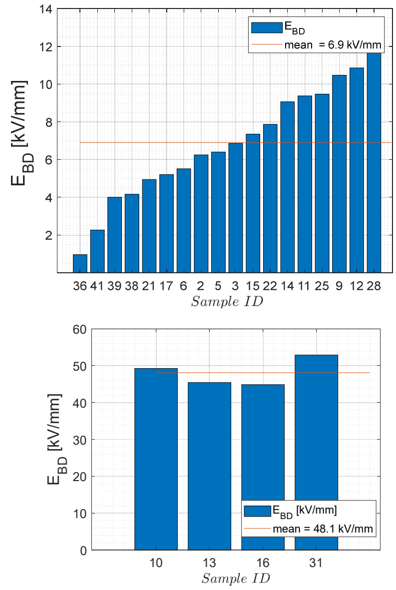

Fig. 11. Dielectric breakdown values under AC (top) and DC field (bottom), obtained for some of the samples

First, we can consider that the low AC breakdown strength values are due to the additional degradation that appears could appear under AC fields, due to partial discharge activity. But, since the voltage application time is short (< 20 s), the degradation of the insulation by carbonization due to the activity of partial discharges can be excluded, as this type of degradation is relatively slow.

The second hypothesis is that the distribution of the electric field is not the same in DC as it is in AC. For example, the difference may be due to the presence of defects in the dielectric, i.e. the probable presence of a voids in the form of air bubbles or possible delamination. Thus, the distribution of the electric field will be different, as, in steady state, the distribution of the field in the different media (in our case dielectric and air) is given by the conductivity of the media, under DC stress or the permittivity of the media, under AC stress. Hence, when applying the voltage, in AC, the distribution of the electric field will be mainly controlled by the permittivity. Thus, a dielectric material with a lower permittivity (e.g, PE or PP), would have exhibited lower dispersion between AC and DC results, which in not the case for the material investigated here, an acrylate with $\varepsilon_r \approx 3.2$, highly influenced by dielectric polarization.

C. Partial discharges measurements and results

The previous results pointed towards the existence of micro-cavities in the material, especially around the printed electrode. To verify this assumption, it was decided to perform Partial Discharge measurements, in air and by submerging the sample in dielectric mineral oil (all tests were performed using an Omicron MPD 600 SN HE471E and all measurements were taken after a calibration at 10 pF). The patterns obtained under an electric field of 6 kV/mm, thus very close to the average breakdown strength, for one minute, under atmospheric conditions and in oil, are given in Figure 12.

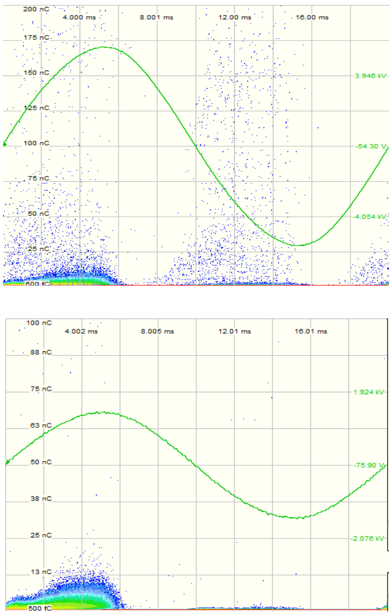

Fig. 12. PD patterns in aid (top) and in dielectric oil (bottom)

The PD pattern due to PD occurring on a triple point could correspond to the pattern of PD in the air [6] whereas the PD behavior of a “simple” void could correspond to the PD pattern found while the sample was submerged in dielectric mineral oil. Thus, we can concur that there are voids or irregularities on the edge of the electrode, that behave like a triple point (electrode-air-dielectric) and that the effect of these voids, once they are filled with oil, is canceled, given the oil’s higher dielectric strength compared to that of air (minimum 10 times higher). Moreover, we can also conclude that there are additional voids inside the dielectric, as emphasized by the second graph in Figure 12.

IV. CONCLUSION

In this work, dielectric properties for different acrylate-based dielectric materials, fabricated using digital manufacturing techniques, is presented. On one hand, the investigated materials had “on demand thickness”, being manufactured as “thin” (7 µm layer) or “thick” (about 500 µm) were found to be “defect-free” by microscopic imagery. On the other hand, dielectric tests have shown that the investigates materials had high PD levels and exhibited rater high DC (> 45 kV/mm) or a rather low AC (< 7 kV/mm) breakdown strengths, thus emphasizing the influence of typical material dielectric properties such polarization vs. conductivity with respect to their electric field behavior.

Furthermore, the use of dielectric tests was found to be a quick and reliable method to assess the quality of thicker inkjet-printed layers. Last but not least, the electrode was found to be the weak point of the printed samples and the element requiring further improvement.

Nevertheless, given that the values obtained for thicker inkjet-printed dielectric layers were obtained without any process optimization, the authors consider that innovative manufacturing techniques have a strong potential, at least for medium voltage applications, thus opening the door for encapsulating power modules or for locally insulating energized nodes, with on demand insulation thickness. With robots now being able to manipulate 3D or inkjet printing heads, the use of these new manufacturing technologies could be part of medium or high voltage in the future.

ACKNOWLEDGMENTS

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