Process optimization for heterogeneous capacitive grading materials by voltage and time monitoring
Trong Trung Le, Rabih Khazaka, Zarel Valdez Nava, Guillaume Belijar, Lionel Laudebat, Sombel Diaham

To cite this version:
Trong Trung Le, Rabih Khazaka, Zarel Valdez Nava, Guillaume Belijar, Lionel Laudebat, et al.. Process optimization for heterogeneous capacitive grading materials by voltage and time monitoring. 2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Dec 2021, Vancouver, Canada. pp.65-68, 10.1109/CEIDP50766.2021.9705444. hal-03876841

HAL Id: hal-03876841
https://ut3-toulouseinp.hal.science/hal-03876841
Submitted on 9 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Process optimization for heterogeneous capacitive grading materials by voltage and time monitoring

Trong Trung Le1,2, Rabih Khazaka1,3, Zarel Valdez Nava2, Guillaume Belijar1, Lionel Laudebat2, Sombel Diahm2
1IRT Saint Exupéry, France, 2LAPLACE, Univ.Toulouse, France, 3SAFRAN SA, France
Email: le@laplace.univ-tlse.fr

Abstract- In the aerospace field, transportation electrification is considered as one of the main solutions that allow the reduction of greenhouse gas levels in the air and slow down the climate change. One of the ways that can allow to reach this goal for electrified systems is the voltage increase and reduce the volume of system onboard. This approach induces consequently induce very high electrical constraints on the insulation materials used in the power conversion systems. These local high electric fields can cause premature failure, by partial discharge activity and insulation breakdown. In order to efficiently reduce the electrical stresses, the design of new system of stress-control encapsulation seem be promising it does not impact the volume of the power module and has a negligible impact on the overall mass. An approach based on the use of low filler ratio composites and the monitoring of the particles (SrtIO3, BaTiO) density by the electric potential to tailor around critical areas where the electric field is high has been validated on simple configuration between two adjacent electrodes. In addition, this approach has been used successfully to apply the FGM on various substrate electrodes of a power module by using a removable electrode in front of the substrate.

I. INTRODUCTION

The trend toward higher power density has been present in all electrical domain, for decades and it projected to continue faster because of asking of reduction of greenhouse gas levels in the air and slow down the climate change. Especially in aerospace field, all systems are much more constrained by their mass. In the development of the more electrical aircraft (total electrical aircraft, hybrid aircraft and hydrogen aircraft), one of main challenge is to increase the voltage and/or reduce the volume of converters. Among increase of power density, also higher voltage semi-conductor devices are becoming readily available, such as Si-based Insulated Gate Bipolar Transistor (IGBT) or SiC-based Metal Oxide Semiconductor Field Effect Transistor (MOSFET). This can like partial discharge activity, up to finally breakdown of insulation in power modules and shutdown the system. The Fig. I shows a schematic cross section view of that type of power module with number of respective triple points highlighted in red circles.

However, this approach will induce extremely high electrical constraints on the insulating materials used in the electrical systems, including the ones closest to the active semiconductors in the power modules. At the heart of the power module, these high electrical fields are strengthen by the geometry imposed by the design, parts fabrication, assembly and packaging methods. One of the most critical regions will be at the junction of two insulating materials, namely the ceramic substrate and the encapsulation, with the metallic track on top of the ceramic substrate. This region is known as the “triple point”, and since the metallization has a sharp geometry, the local electric fields are non-homogeneous and divergent.

In this paper, the impact of the applied electric potential and its duration will be presented in order to evaluate and optimize the process to allow an electrodeposition with a homogeneous thinness of stress-control layer.

In the later strategy, beside finding new materials formulations, it is possible to lower local electrical fields at the triple point by modifying locally the electrical properties. This is known as electrical stress-control or field-grading. This can be achieved by applying different layers of materials with
different intrinsic properties or by building a Functionally Graded Material (FGM). In latest publication, our method with using of electrodeposition phenomena allows to build FGM in high electric field regions of power module. Firstly, the described method was success cover on the high positive potential of two copper electrodes on top of a DBC. The results show an increasing of withstand voltage on track-to-track surface breakdown by at least 70% when compared to a neat epoxy encapsulation Erreur! Source du renvoi introuvable. Erreur! Source du renvoi introuvable.. To more nearly the real power module, two methods was proposed to cover the main triple points in a more complex tested DBC structured and one was validated Erreur! Source du renvoi introuvable.. One removable electrode was added on top of DBC substrate with distance de 5mm during the FGM application by electrodeposition. This external electrode could be removed prior to the curing process of the polymer composite. All of electrode was cover by a homogenous thickness of accumulation layer. Evolution of thickness was observed qua-similar with the case of using two parallel electrodes. In order to evaluate and optimize this process, the main aim of this paper will present our experimental of electrodeposition with various of applied voltage. Then the results allow us not only to optimize the process but also understand more the mechanic and phenomonal of electrodeposition.

III. EXPERIMENTAL

Our process of electrodeposition is based on applying an electrical field on two parallel electrodes with the mixture of particles and epoxy resin is pour between. For process optimization, two copper parallels electrodes placed by 1mm using insulating spacer are used. The two electrodes are attached on a glass by using a transparent epoxy resin. (Photo For all experiments, a di-glycidyl ether of bisphenol F (DGEBF) thermosetting epoxy resin system (EP 630, Polytec PT GmbH) was used. The hardener is an amine type with a ratio of 10:1 (resin: hardener). After curing, the epoxy has a density of 1.23 g/cm$^3$. Strontium titanate (SrTiO$_3$) particles with a density of 5.11 g/cm$^3$ were added at 10 vol% and mixed in a planetary mixer. The polyhedral-shaped particles have an average diameter of 600 nm.

Fig. 2: a) Test vehicle with two parallel electrodes for process optimization. The distance between the two electrodes is fixed to 1mm. b) Installation of camera to observe the electrodeposition. Microscopic observations during the electric field application are done from the transparent glass side using Keyence digital microscope and the current is measured between the two electrodes with a Keithley 2410 Sourcemeter.

The impact of the applied electric potential on the composite with filler ration fix was evaluated under various voltages of 67V, 125V, 250V and 500V. In other hand, a higher tension of 1500V was tested with the two parallel electrodes and in a real substrate DBC.

III. VARIOUS EVOLUTION OF FILLED RESIN AND OPTIMAZATION PROCESS

A. Various evolution of composite resin under various field.

For composites with low particle concentration (10 %), the fluid “turbulence” takes place at early time after the polarization in almost all the regions between the two electrodes. The electrostatic force attracts the particles (negatively charged) at the high voltage electrode to form a dense particles layer. The shear stress induced at the interface between the dense layer and the fluid in motion can remove some particles from the dense layer and hence acts in an opposite way to the electrostatic forces. This limits the electrodeposited layer growth rate and its final thickness. During the time, the horizontal limit of the turbulent motion region (green bars) is decreased gradually in an opposite way to the dense layer thickness where no turbulent flow appears (red bars) until reaching a quasi-equilibrium after about 1400s. The impact of applied electric field on the evolution of gradient material was evaluated and the recorded mages under after 1200s and 2700ss are presented in Fig.3.
Thus, the thickness of the dense layer increases faster for higher applied electric potential indicating that electrostatic forces became more dominant at higher voltages. Oppositely, the horizontal limit of the turbulent motion region in green bars is decrease faster with higher applied potential and inversion. We also noted as the higher external field as the particles concentration in the accumulated layer (red bars) is higher and in the resin in motion (green bars) is lower. The resin in motion after 2700s applying of 500V/mm shows an extremely low particles concentration as figure 3.d. The results show that the same behavior with all levels of potential is observed in the composite for the various applied electric potentials. In all cases, the fluid turbulence takes place at early time after the polarization in almost all the regions between the two electrodes. The thickness of the dense layer increases faster for higher applied electric potential indicating that electrostatic forces dominate the shear stress induced by the liquid motion at higher voltages and inversion. Otherwise, the faster turbulent under higher field than 500V/mm applied potential seems cannot achieve a homogeneous layer.

B. Quasi-stabilization at interface of electrodeposited layer.

In the latest publication, the accumulation of particles on the higher potential was explicated because of influence of some phenomenal of electrophoresis, electrophoresis, electrosorption and electrohydrodynamic (EHD). This explication is not enough to explain the quasi-stabilization state after 25min.

Indeed, a layer of lower concentration of particles in comparison with homogenous filled resin at interface of accumulated layer was observed and get our attention. In this layer the particles were moving different without the turbulent. A quasi-stabilization stage with some particles is pulled to accumulation layer and compacted when some other is tear to back the moving resin. This phase seems be an equilibrium between the accumulation and the dispersion by the two different forces, one is electrophoresis force and other is because of monodisperse concentration. In fact, the accumulation is due by electrophoresis where particles are displaced within a liquid medium under the application of an electrostatic force (i.e. the Coulomb force) on the compound. charged particles present an arrangement of charges in the interface called the electrical double layer (EDL). In other hand, at the accumulation layer with higher concentration particle crowding produces hydrodynamic interactions between particles, resulting in significant positive deviation. Many models have been proposed to describe the concentration dependence of the relative viscosity of concentrated suspensions. One of the most useful expressions is the semi-empirical equation of Krieger and Dougherty for monodisperse suspensions. The relative viscosity variation as function of filler ratio according to Einstein and Krieger-Dougherty was presented in some Erreur! Source du renvoi introuvable. In fact, charged particles present an arrangement of charges in the interface called the Electrical Double Layer (EDL). As two particles approach each other, the overlapping of double layers leads to long-range, electrostatic repulsive forces. The distortion of the EDL by the shear field leads to an increase in the viscosity due to increased energy dissipation. This effect was first considered by Smoluchowski and is called the primary electroviscous effect Erreur! Source du renvoi introuvable.

C. Influence of various field electrodeposition.

The normalized conductivity (conductivity/conductivity t0) and the dense electrodeposited layer thickness under the various extension are presented in Fig.4. We can see that the normalized conductivity during the first minutes followed by an increase or a stabilization of the value. For the thickness of accumulation layer, the evolution shows an increase during the first minutes followed by a quasi-stabilization of the layer thickness (from 14min to 25min) until the end of the process after 45min. In the applied electric potential evaluated range, the time to reach equilibrium is not dependent of the external applied field and the dense layer is thicker for higher potentials at the end of the process (45min).
During the phase where thickness increases, the electrostatic force that attracts the particles to the high voltage electrode dominates the electro hydrodynamic shear stress induced by the motion of the fluid. On the other hand, the quasi-stabilization phase reflects a quasi-equilibrium between the two controversial forces. The quasi equilibrium between the two forces can be due to the decrease of the viscosity of the fluid once a part of the particles are deposited on the high voltage electrodes. Accordingly, the viscous forces in the liquid are reduced and the flow motion related to electro hydrodynamics mechanisms is promoted. Hence, shear stress at the interfaces due to the fluid motion became sufficiently high to remove particles that are attracted by electrostatic forces. A second assumption based on the decrease of the internal field in the region between the dense electrodeposited layer and the ground electrodes can also contribute to the explanation of the quasi-equilibrium between the two opposed forces. Since dense particle layer is more resistive than composite with low density and particles are negatively charged, the electric field in the region in motion is reduced during the increase of the thickness of the dense layer. Once a certain level is reached, the electrostatic attractive forces will be more significantly reduced than the shear stress induced by the liquid motions and an equilibrium between the two forces is reached.

Finally, the growth rate of the dense layer on the high voltage electrode as function of the external electric field for a composite with 10%vol filled ratio is presented in Fig.5. The values fit well with a polynomial form:

\[ y = -4e^{-7x^2} + 0.0006x. \]

C. Process optimization.

The growth rate of the dense layer on the high voltage electrode increases as the voltage increases. Depending on the targeted final thickness of the dense layer and the process time constraint, the voltage can be choose in the range between 67V and 500V (for 1mm space between the two electrodes) and the time period between 60 and 1400s. However, in order to avoid sharp variation of the accumulation layer in the composite, the use of high fields (>250V/mm) for long periods (>1000s) is not recommended. The higher tension of 1500V AC isn't recommended to avoid danger of thermal runaway because of high injection current. This thermal runaway in the case of apply the electrodeposition for a DBC substrate is present in Fig. 6.

IV. CONCLUSION

Our process of electrodeposition allows to apply a homogenous layer of stress-control surrounding high field region around the triple point. This paper presented the mechanic and electrodeposition phenomenal principal of our process with a clear explication.

Depending on the targeted final thickness of the accumulation layer, the voltage can be choose in 67V and 500
during a period between 60s and 1400s fit with the equation: \( y = -4e^{-7x^2} + 0.0006x \). Further works need to be carried out the evaluation of process using the removable electrode with optimization time and voltage, verify the gain in performance obtained these FGM in a real module power.

REFERENCES


