Engineered PMMA-CuO nanocomposites for improving the electric arc interruption process in electrical switching applications

Venkatesh Doddapaneni[1,*], Rudolf Gati[2], Muhammet S. Toprak[1,*]

[1]Department of Applied Physics, KTH Royal Institute of Technology, Roslagstullsbacken 21, SE106 91 Stockholm, Sweden
[2]ABB Switzerland, Corporate Research, Segelhofstrasse 1K, 5405 Baden-Dattwil, Switzerland

Abstract

Polymer-based nanocomposites (PNCs) display fascinating functionalities to be useful in electrical switching applications like circuit breakers, switch gears, etc. These PNCs are fabricated by incorporating nanoparticles (NPs) into a polymer by *in-situ* polymerization. When the PNCs interrupt the high energetic fault currents generate between the two contacts in a circuit breaker, they outgas (ablation) chemical species and cooling gases, which change the thermodynamic properties of the arcing environment leading to quench the electrical arcs quickly. Two PNCs are fabricated with different wt% of oleic acid modified CuO NPs and a polymer matrix i.e. poly methyl methacrylate (PMMA). These PNCs are tested with the electrical arcs of a prospective current of 1.6 kA generated in the test-setup. The electrical signals (arc current and voltage) and computed dissipated enegy i.e., $\int i(t)V(t)dt$ help to understand the effect of PNCs on the electrical arcs. In addition to that, the computed joule integral and mass loss of the PNCs due to outgassing is reported. The re-depositions of the chemical species are analyzed by using Fourier transform infrared spectroscopy (FTIR) and the morphological changes on the surface of outgassed PNCs are analyzed by using scanning electron microscopy (SEM). These results help to understand the effect of PNCs on the arc interruption process in circuit breakers.

Introduction

Polymeric materials generate vapors due to the broad range radiation produced by electric arcs during the interruption of high energetic fault currents in electrical switching applications [1-3]. This vapor generating process is called as outgassing process[4]. According to the several experimental and theoretical investigations, these generated vapors help to improve the convective arc interruption process [5-9]. Therefore, the outgassing process mostly depends on the percentage of radiative and thermal energy absorbed by the solid polymeric materials. Reported experimental and modelling results show that, radiative energy transfer (RET) is dominant in the outgassing process leading to the arc interruption [10] [11]. Therefore, the necessity of improving the radiation absorption of solid polymeric materials found and could be developed by utilizing the latest material science developments [12]. In particular, the intense UV radiation absorption of PNCs can be improved in order to facilitate the breakdown of PMMA monomer into CH, H_2, C_2H_2, CO_2, H_2O and CO species leading to better arc interruption capability[13].

There are several physical mechanisms i.e. photochemical, photothermal and their combination that are involved in the arc interruption processes [14, 15]. The photochemical is a direct bond breaking mechanism of chemical species due to electron excitation. The photothermal is a bond breaking mechanism of chemical species due to pyrolysis. Since electric arc generates broad range radiation towards PNCs, mostly, all the mechanisms work simultaneously. PNCs could improve these mechanisms due to NPs in polymer matrix. NPs in PNCs could absorb the UV radiation absorption and disperse the energy towards PMMA monomer chains, help to break down the chemical bonds[16, 17].

The PNCs are fabricated by incorporating suitable radiation absorbing NPs as CuO into a polymeric matrix by *in-situ* polymerization, reported in our earlier work[16]. Two PNCs is fabricated by incorporating oleic acid (OA) modified cupric oxide (CuO) NPs into PMMA is reported[18]. CuO nanoparticles were chosen to fabricate PNCs in order to maximize the absorption of radiation emitted from strong copper arc generated by the copper electrodes in the real circuit breaker system at KTH - Smart Grid Component Laboratory and the polymer matrix i.e., PMMA was chosen based on the material properties observed during arc interruption process. In addition, PMMA is an excellent insulator, environment friendly and economically good alternative to other polymers[19, 20]. In this work, we reported the electrical measurements, with the electrical arc, outgassed masses during the interaction with the electrical arcs and morphology of outgassed PNCs and PMMA. Besides that, we performed FT-IR spectroscopy measurements on the outgassed depositions on the PNCs. All these experiments help to better understand the arc interruption capability of PNCs.

Experimental results and discussion

All the samples shown in Figure 1 are tested for the electric arc interruption process. The designed experimental test-setup comprises of high power source circuit and was explained in our earlier work[13, 16]. Typically, It consists of a damped RLC circuit with a capacitor bank of 16 mF, an inductor of 496 μH for generating the electrical arc of 1.6 kA. In the same circuit, a thyristor is connected for discharging the capacitor bank. The charging voltage i.e. 450 V for capacitor bank is maintained for all the tests in order to generate the electrical arcs with a prospective peak current of 1.6 kA. The recorded oscillograms show variation in arc current and voltage during the tests with PNCs and their capability in arc interruption process. The mean voltage values computed and shown in Table 1 proving that addition of NPs in PMMA, increased the voltage build-up due to outgassed chemical species in the arc region. It is possible to understand from Figure 2, how outgassed chemical species directed towards electric arc to reduce arc core temperature and led to electric arc interruption process.

In the oscillograms shown in Figure 3, the arc quenching time and the arc voltage is correlated with the reported UV-radiation absorbance measurements[18]. There is no significant difference observed between PMMA and PNC_1. In the case of PNC_2, a relatively high arc voltage is observed, which led to limit the electric arc current and time. The arc is extinguished approximately 0.37 ms faster than PNC_1 and PMMA. It is analyzed from our previous measurements that, all these arc are in high voltage state where they are not really stable shown by the voltage spikes. According to the computed dissipated energy values shown in Figure 4, they are nearly same for all the samples, while the outgassed mass values shown a difference among them. It is noticed that the strong depositions of PNC_2 during the interaction with the electric arc, caused to record a lowest mass loss in compared to PMMA and PNC_1.

The deposited chemical species were analyzed by using FT-IR spectroscopy. It is found that the signature of the functional groups shown in Figure 5 such as C-H (2995-2862, 1141, 741cm^{-1}), C-C (1431 cm^{-1}), N-O (1476cm^{-1}), C=O (1726 cm^{-1}) and several other peaks shown in our previous work lead to electric arc interruption process[21].

Surface morphology of the outgassed PNCs was observed by using optical microscopy. It is clearly evidenced that the addition of NPs in PMMA led to increased erosion density and blisters on the surface of the PNCs. From the theory and experiments about the arcing process between the cathode and anode, the highly energetic electrons drive from cathode to anode[22, 23]. Under these conditions, it is possible to have better outgassing towards anode side on the PNCs in compared to cathode side, as shown in Figure 6. In-between the electrodes, PNCs seen as smooth due to surface recodifications of PNCs due to high intensity of electric arc.

Conclusions

PNCs consisting of PMMA and CuO NPs are tested successfully to see their impact on the electrical arcs generate in electrical switching applications. The experimental evaluation is shown that, PNCs were able to absorb improved radiation from the high-energy electric arc generated between the copper electrodes. The absorbed energy improves the outgassing process helpful to raise operational limits in the circuit breaker. The arcing time and arc voltage correlates with the radiation absorbance of the PNCs and PMMA and noticed that there is no significant difference in the electrical signals for PMMA and PNC_1 (with low wt% of NPs). Surface morphology of PNCs are observed and reported. All these results are used to understand the impact of PNCs on the electric arc interruption process in electrical switching applications where outgassing polymers are necessary.

References

[1] E.Z. Ibrahim, The ablation dominated polymethylmethacrylate arc, Journal of Physics D: Applied Physics 13(11) (1980) 2045-2066.

[2] P.F. Hettwer, Arc-Interruption and Gas-Evolution Characteristics of Common Polymeric Materials, IEEE Transactions on Power Apparatus and Systems 101(6) (1982) 1689-1696.

[3] E. Jonsson, M. Runde, G. Dominguez, A. Friberg, E. Johansson, Arc quenching performance due to ablation; comparison between four common polymers, 26th International Conference on Electrical Contacts (ICEC 2012) (2012) 41-44.

[4] C. Rumpler, A. Zacharias, H. Stammberger, Low – voltage circuit breaker arc simulation including contact arm motion, 27th International Conference on Electrical Contacts (2014) 290-294.

[5] C.B. Ruchti, L. Niemeyer, Ablation Controlled Arcs, IEEE Transactions on Plasma Science 14(4) (1986) 423-434.

[6] T. Onchi, M. Isozaki, S. Sugiyama, Y. Tanaka, Y. Uesugi, Onchi, Influence of polymer and metallic vapour on low voltage arc, International Conference on Gas Discharges and Their Applications 17 (2008) 101--104.

[7] Y. Tanaka, Effect of polymer ablation on temperature decay of thermal plasmas using induction thermal plasma irradiation technique, International Conference on Gas Dischargees and Their Applications 17 (2008) 89--92.

[8] Y. Tanaka, Y. Takeuchi, T. Sakuyama, Y. Uesugi, S. Kaneko, S. Okabe, Numerical and experimental investigations on thermal interaction between thermal plasma and solid polymer powders using induction thermal plasma technique, Journal of Physics D: Applied Physics 41(2) (2008) 025203.

[9] H. Ito, T. Sakuta, T. Kobayashi, Measurement of arc properties and spectrum intensity in AC arcs surrounded by plastics, Electrical Engineering in Japan 140(1) (2002) 38-47.

[10] Y. Cressault, J.M. Bauchire, D. Hong, H. Rabat, G. Riquel, F. Sanchez, A. Gleizes, Radiation of long and high power arcs, Journal of Physics D: Applied Physics 48(41) (2015) 415201.

[11] V.V. Nossov, B. Hage, B. Jusselin, C. Fievet, Simulation of the thermal radiation effect of an arc on polymer walls in low-voltage circuit breakers, Technical Physics 52(5) (2007) 651-659.

[12] S. Li, M. Meng Lin, M.S. Toprak, D.K. Kim, M. Muhammed, Nanocomposites of polymer and inorganic nanoparticles for optical and magnetic applications, Nano Reviews 1(0) (2010) 1--19.

[13] V. Doddapaneni, J. Magnusson, A. Bissal, H. Edin, M.S. Toprak, R. Gati, Spectroscopic investigations of the ablated species from the polymers exposed to electric arcs in air, 2015 3rd International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST) 3 (2015) 337-340.

[14] T. Lippert, Laser Application of Polymers, Advanced Polymer Science 168 (2004) 51--246.

[15] N. Bityurin, B.S. Luk'yanchuk, M.H. Hong, T.C. Chong, Models for laser ablation of polymers, Chem. Rev. 103(2) (2003) 519-52.

[16] V. Doddapaneni, M. Saleemi, F. Ye, R. Gati, M.S. Toprak, Engineered PMMA-ZnO nanocomposites for improving the electric arc interruption capability in electrical switching applications: Unprecedented experimental insights, Composites Science and Technology 141 (2017) 113-119.

[17] V. Doddapaneni, M. Saleemi, F. Ye, R. Gati, M.S. Toprak, On the electrical arc interruption by using PMMA/iron oxide nanocomposites, Materials Research Express 3(10) (2016) 105043.
[18] V. Doddapaneni, Y.C. Zhao, F. Ye, R. Gati, H. Edin, M.S. Toprak, Improving Uv Radiation Absorption by Copper Oxide NPs/PMMA Nanocomposites for Electrical Switching Applications, J. Powder Metall. Met. Ceram. 54(7-8) (2015) 397-401.
[19] S. Affolter, Long-Term Behaviour of Thermoplastic Materials, 41(0) (2008) 1--21.
[20] K. Chrissafis, D. Bikiaris, Can nanoparticles really enhance thermal stability of polymers? Part I: An overview on thermal decomposition of addition polymers, Thermochimica Acta 523(1-2) (2011) 1-24.
[21] L. Niemeyer, Evaporation Dominated High Current Arcs in Narrowi Channels, IEEE Transactions on Power Apparatus and Systems 97(3) (1978) 950--958.
[22] S. Ramakrishnan, A.D. Stokes, J.J. Lowke, An approximate model for high-current free-burning arcs, Journal of Physics D: Applied Physics 11(16) (1978) 2267-2280.

Figures:

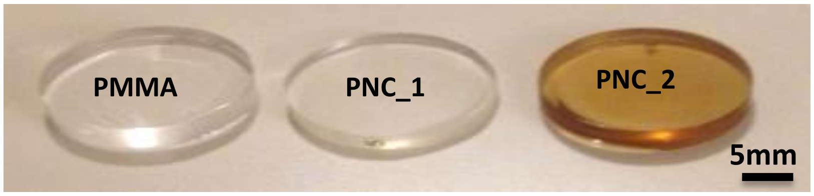

Figure 1. Optical micrograph of the PMMA and PNCs.

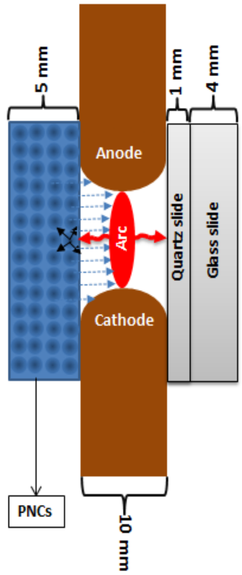

Figure 2. Illustration of the PNCs and experimental test-setup used for the tests with electricals arcs.

Table 1. Wt% of CuO NPs used for PNCs and computed mean average voltage rise from electrical signals.

Sample Name	PMMA	PNC_1	PNC_2
CuO Wt%	---	0.0017	0.024
Average voltage [V]	171.7	172.36	185.91

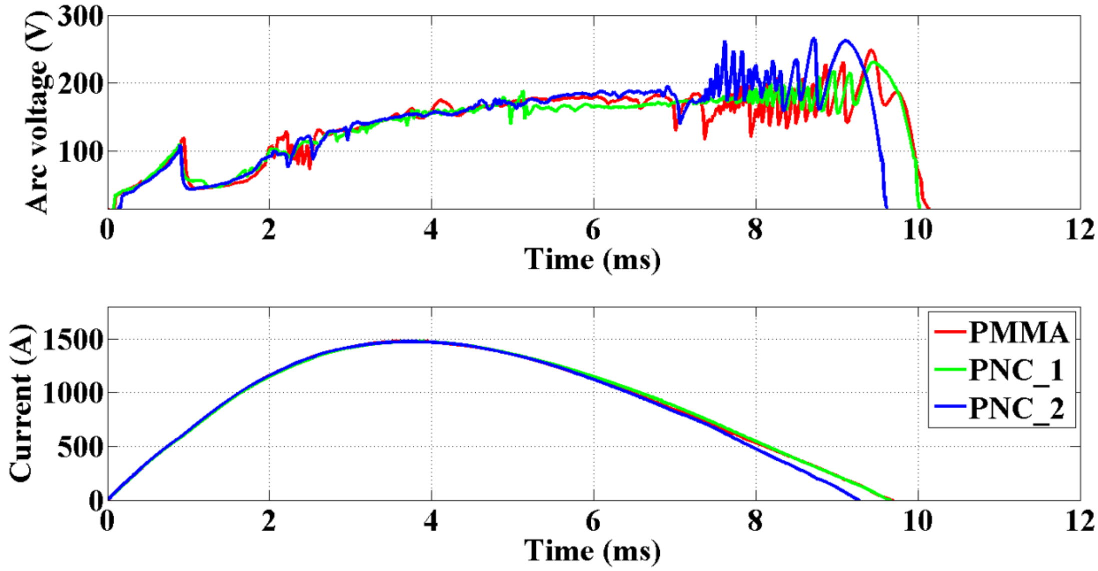

Figure 3. The electrical signals of the tested PNCs and PMMA.

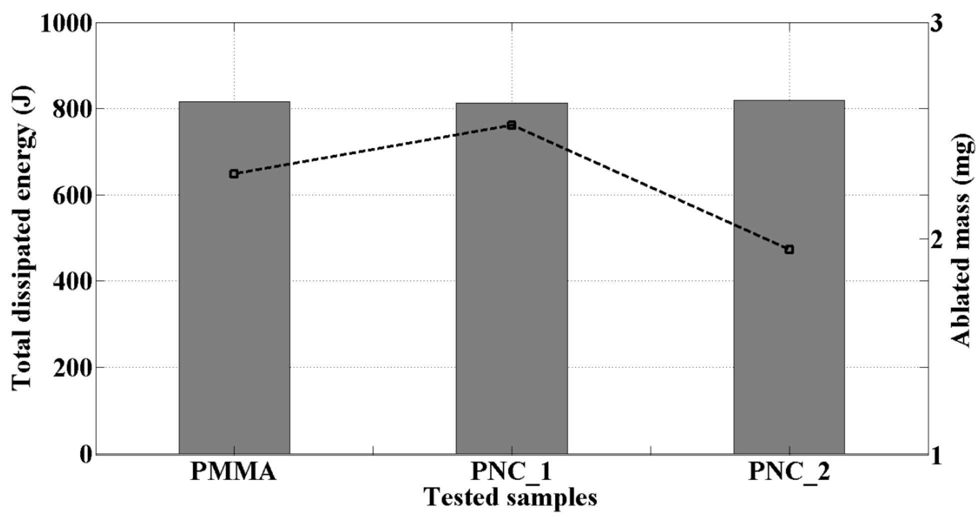

Figure 4. Total dissipated energy (bar plot) and recorded ablated mass (dashed line) using the tested samples i.e. PMMA and PNCs.

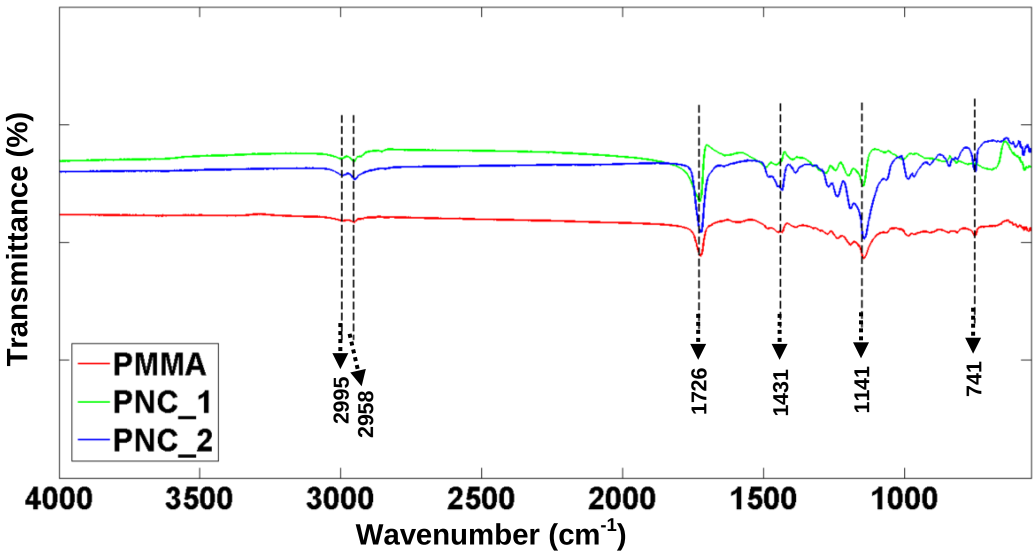

Figure 5. FT-IR spectrum of the deposited outgassed chemical species on the PMMA and PNCs.

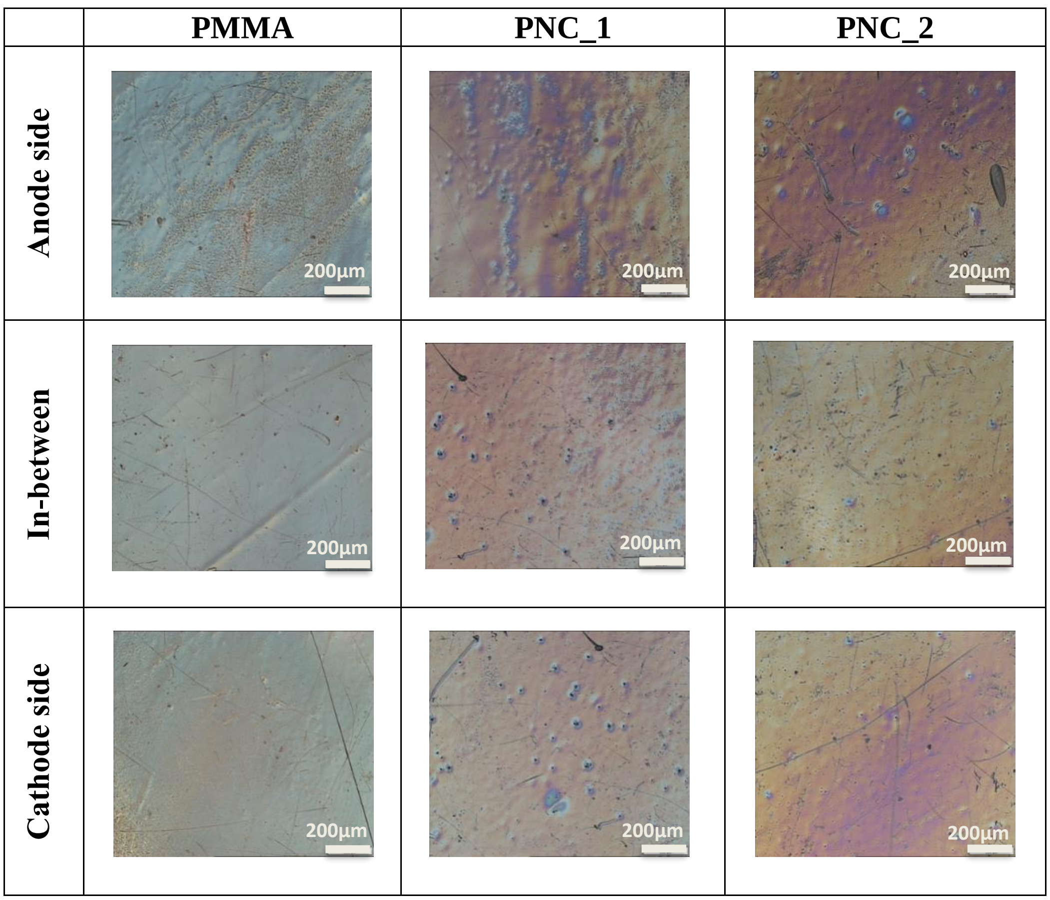

Figure 6. Optical micrographs of the outgassed PMMA and PNCs after three discharges in different locations.