Journal of Ceramic Processing Research. Vol. 13, Special. 2, pp. s233~s236 (2012)

J O U R N A L O F
Ceramic Processing Research

Evaluation of partial discharge resistance of insulating sheets produced in Saudi Arabia under alternating stress

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This paper deals with the comparison of partial discharge (PD) characteristics of three kinds of insulating sheets produced by the local industry in Saudi Arabia; namely polycarbonate (PC), poly-methylmetacrylate (PMMA) and phenoplast resin (Bakelite). These were exposed to PDs under the IEC (b) electrode system, and the comparison was judged by the discharge onset; discharge propagation area, PD magnitude, surface erosion and elemental analysis of eroded zones. Results show that PD inception voltage is inversely proportional to the sample's relative permittivity. For higher permittivity samples, the eroded area under a constant voltage is larger, while PD activity is also augmented significantly. The erosion depth was found to be deeper in Bakelite. In this case, the scanning electron microscope images show a larger concentration of scattered debris of the base material on the eroded area. Whereas, EDX elemental analysis of these areas exhibits presence of the native matrix for PC and PMMA sheets, a large content of copper and zinc was found on the Bakelite sheet, which also displays the erosion of the electrode.

Key words: Surface discharge, Polymer insulating sheets, Partial discharge, EDX analysis, Surface erosion.

Introduction

Most of the electrical apparatus is designed to operate with composite junctions such as solid / air (gas) or solid / liquid. Typical examples are transformers, cables, switchgear and capacitors etc. The introduction of such components, not only controls the electrical stress but it also lengthens the discharge path and it provides the barrier effect. In addition, these composites also work as mechanical supports. During the life time of the equipment, several types of discharges occur on the interface of these junctions. If these are not contained, they can lead to serious surface erosion and the final breakdown of the insulation. Hence knowledge of the initiation and propagation of these discharges are of paramount importance for the design optimization of high voltage equipment.

Numerous studies have been reported on the phenomena of the surface discharge on polymer sheets [1-5] and on biodegradable material surfaces [6]. More recently, several types of commercially marketed polymer sheets are being produced in Saudi Arabia. Based on the purity of resins and the clean manufacturing processes used, several sheets were acquired and subjected to preliminary tests and their dielectric strength was compared. Of these, polycarbonate (PC), polymethyl methacrylate (PMMA) and phenolic resin (Bakelite) sheets, were found promising and were selected for further detailed evaluation. This paper presents results pertaining to their resistance toward surface discharges when they were subjected under alternating power frequency stress. These sheets were exposed to a constant level of high voltage under IEC(b) electrode system, and the comparison was judged by the discharge onset, propagation area, PD magnitude, surface erosion, followed by elemental analysis of eroded zones. The implications of these results are presented with analysis and discussion.

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Experimental techniques

Examined samples were in the form of three kinds of insulating sheets, PMMA, PC and Bakelite with 60 Hz relative permittivity (ε_r) at 20 °C of 3.7, 3.2 and 6.0, respectively. All samples were plaques of 3.0 mm thickness and cut into the square dimensions of 100 mm × 100 mm. The experimental system consisted of the IEC(b) electrode system as shown in Fig. 1. The upper electrode was brass (6-mm diameter with the edge turned at 1-mmR) and a lower stainless steel electrode. Their endurance was investigated by applying 60 Hz ac voltage fixed at 15.0 kV_{rms}. The sample surface was exposed to PDs generated in the air gap between the rod electrode and the sample for the fixed periods of 6 hours, 19 hours and 48 hours. The eroded surface area was measured based on its average diameter. To determine the PD onset level and intensity as a function

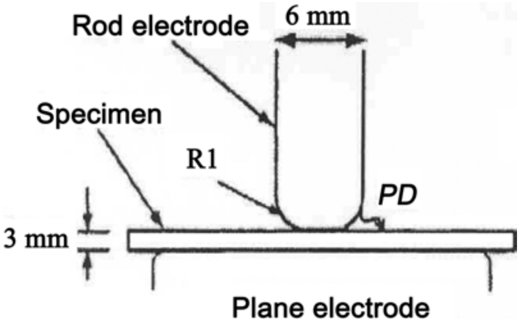


Fig. 1. IEC(b) electrode configuration for surface discharge degradation test.

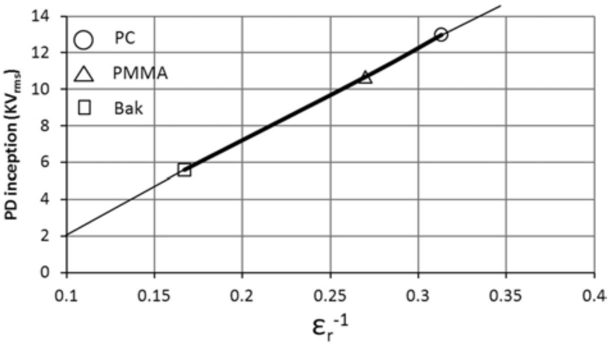


Fig. 2. PD onset voltage as a function of the reciprocal of permittivity.

of time, a conventional PD system based on IEC-60270 was utilized. The elemental analysis of debris emitted from the eroded area was carried out using the EDX module of scanning electrode microscope (Jeol JSM-6360-A, Japan). It was used in high vacuum mode in order to avoid sample charging. Secondary electron imaging analysis was performed to study the surface morphology at an accelerating voltage of 20 kV. SEM micrographs were captured for analyzing surface condition, at a magnification of ×500.

Results and analysis

Partial discharge trends

The partial discharge onset voltage (V_{os}) is defined as the voltage at which PDs above 15 pico Columb (pC) are first detected which was measured by ramping the voltage with a constant rate of about 0.5 kV/s at 60 Hz. After that, the voltage was maintained at 15.0 kV and the number of PD pulses and net virtual charge being emitted was scanned for a period of 700 s. Fig. 2 shows the V_{os} as a function of ε_r^{-1}. It is clear that it is a linear relation and shows a strong capacitive effect of the insulating sheets and substantiates this effect reported earlier under the application of DC / impulse voltages [5] as well as in biodegradable polymers [6]. Thus the electric field intensity in the miniscule air gap, where the PDs occur the most, is enhanced directly in proportion to ε_r of the sample. Thus, the capacitive division across the air / solid composite holds under applied alternating stress. A linear relation between the applied voltage and ε_r^{-1} proves, that the PD is initiated in the air gap when the potential difference in the air gap between the rod electrode and the solid's surface reaches a specific PD onset threshold value.

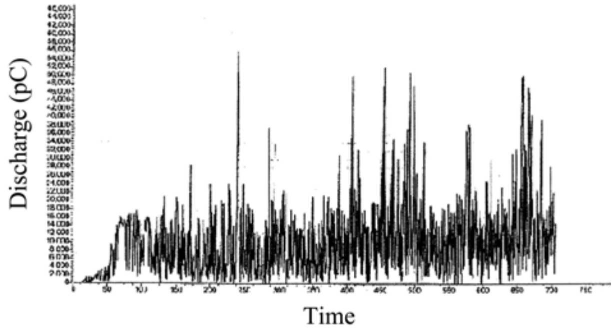


Fig. 3. Variation of PD as a function of time on the surface of Bakelite.

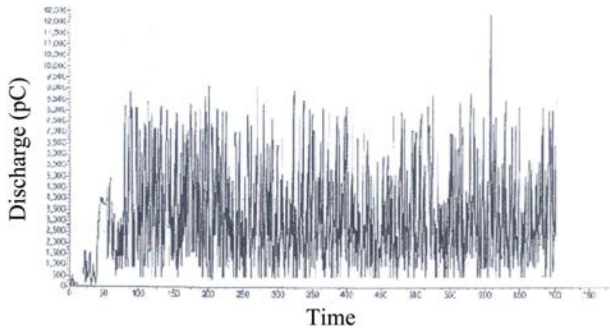


Fig. 4. Variation of PD as a function of time on the surface of PC.

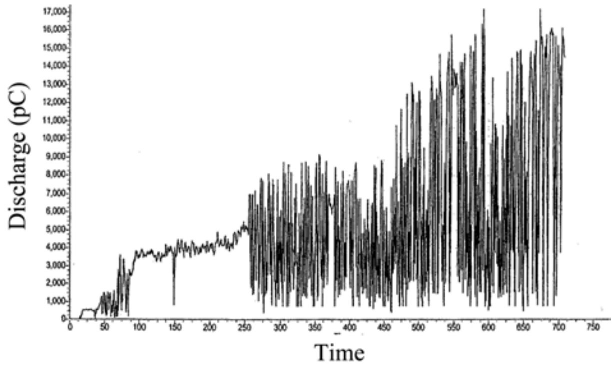


Fig. 5. Variation of PD as a function of time on the surface of PMMA.

Figs. 3-5 display real-time PD spectrums in the three insulating polymers. It is clear that in case of Bakelite (Fig. 3), the PD pulse activity takes a strong repetitive course with very large pulses. The average charge of these pulses was around 9,500 pC while the pulses oscillated in a range of 14,000 to 60,000 pC. This strong activity of the PD can lead to a severe degradation of the Bakelite surface. In the case of PC, the PD development process, takes a uniform course with nearly equal amplitude repetitive discharge peaks (see Fig. 4). The average charge of these pulses is ~ 3,500 pC, whereas the largest pulse occurred with a charge value of 10,000 pC.

The trend in PMMA was different than in the other two. Initially there was a constant discharge current flow and after 200s of voltage application an intense pulse activity was initiated which increased in amplitude with time. Near the end of 700s period, the pulses with a charge value of ~ 16,000 pC emerge as shown in Fig. 5. It is clear that on PC and PMMA, the PD activity is not as severe as on the surface of Bakelite. Whereas the surface morphology of PC and PMMA is with smooth structure, the Bakelite surface is slightly corrugated. Either it is the surface topology or the chemical composition of the polymer's base matrix which reacts with the discharge plasma.

Comparison of surface erosion

Fig. 6 illustrates the comparison of the eroded surface diameter due to the PD endurance as a function of aging time. The scatter on each data point is an average of three readings. It is clear that the discharge expands the largest on the surface of PMMA. The smallest area which eroded was on the Bakelite surface although the depth of erosion (not shown here) was much larger as compared to other two polymers. However, due to its higher permittivity, the stress level is smaller on in its surface than on the other two. The deeper degradation can be attributed either to its slightly corrugated surface, where beside surface discharge, the void discharge is also possible in combination, thus making not only the PD activity more intense, but the chemistry of reaction of plasma species so developed with the matrix of Bakelite shall also differ appreciably. These aspects are explained with the elemental analysis of debris broken out of the surface of these polymers, due to the surface degradation.

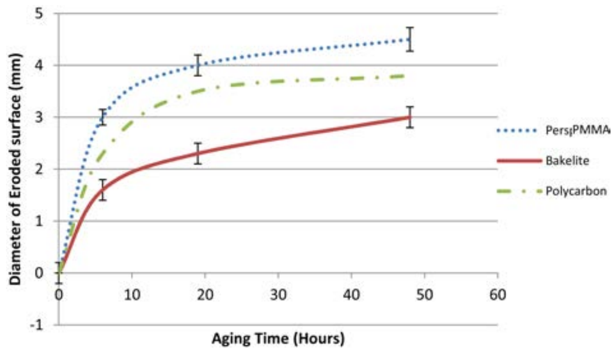


Fig. 6. Erosion diameter as a function of aging time.

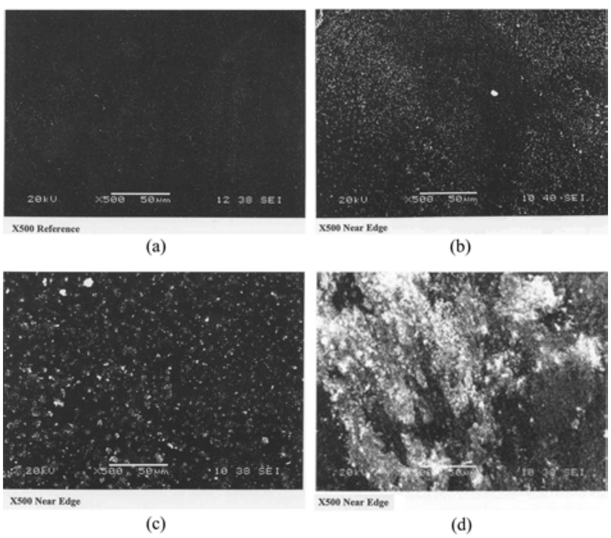
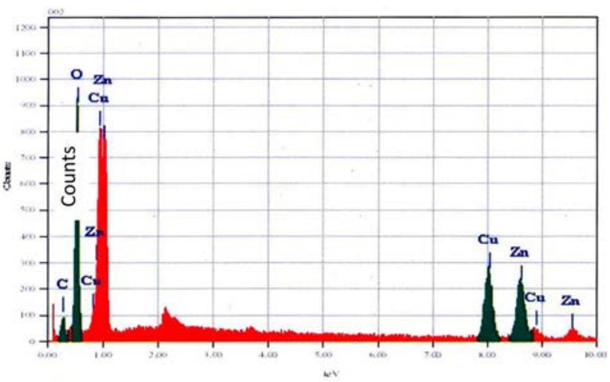


Fig. 7. Surface profile of (a) unaged sample, (b) PMMA, (c) PC, and (d) Bakelite.

Elemental analysis of eroded surfaces

Using the EDX module of SEM, the elemental analysis of the eroded area under the edge of the electrode, where the PD intensity was the severest, was carried out along with the capture of images under high magnification. Fig. 7(a-d) exhibits the surface images of the three polymers subjected to the PD activity. Fig. 7(a) shows the surface sample of one of the unaged samples which serves as the reference. The other two unaged samples (not shown here) have almost the same image profiles. In the case of PMMA (Fig. 7(b)) the erosion of surface in the form of whitish debris is obvious. The size of this debris amounts about few mm. The images captured 2 mm away from the edge (not shown here) exhibit their size to be around 10 mm while the number density of debris is comparatively much less. This shows that as the erosion proceeds the debris are fragmented due to high energy arcs of the discharge and those which are away from the hot spot remain less fragmented. The elemental analysis of the debris revealed the presence of C and O_2 which are the main constituting ingredients of the matrix of the polymer.

Fig. 7(c) shows the image captured near the electrode edge for polycarbonate. Although the number density



Element	(keV)	mass%	Error%	At%	Compound	mass%	Cation	K
C K	0.277	7.25	0.31	17.78			1.3057	
O K	0.525	28.84	0.26	53.05			31.3474	
Cu K	8.040	30.68	1.21	14.21			32.3373	
Zn K	8.630	33.23	1.55	14.96			35.0096	
Total		100.00		100.00				

Fig. 8. Elemental composition of debris of Bakelite found at the edge of electrode.

of fragmented debris in this case is less than under PMMA, their size amounts to around (1-10) μm which shows more resistance of the PC toward surface erosion due to the PD activity. The elemental analysis also revealed the presence of C and O_2. H_2 is also present but EDX cannot show elements with $Z \leq 12$.

Fig. 7(d) illustrates the very intense degradation of the Bakelite surface near the edge. This degradation was found to be fairly strong even at a distance of 4 mm away. Fig. (8) illustrates the elemental analysis of the worn out area close to this edge. In this case, beside the elements of the base polymer, large contents of Cu and Zn were also present which have certainly been leached out of the brass electrode used. This shows that the high energy plasma species interact not only with the base polymer, but coupled with the high energy arcs, react with the overhead metal, as well.

Conclusions

Using the IEC(b) electrode system, the impact of the surface discharge on three types of insulating polymer sheets, namely PC, PMMA and Bakelite were studied and leads to the following results:

1. The PD inception voltage is inversely proportional to the sample's relative permittivity and thus strongly exhibits the capacitive distribution of electric stress across the composite polymer.
2. The sample with the higher permittivity exhibits a higher surface discharge.
3. The corrugated surface of polymer reduces the radial propagation of the discharge but experiences more intense PD at the dips of surface which can lead to a deeper erosion and fragmentation of worn out debris.

Acknowlegement

The authors are thankful to the Research Center, College of Engineering for supporting this research project.

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