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이축연신 폴리프로필렌 필름 Capacitor의 Grape-clustering Process에 관한 연구

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Grape-clustering Process of BOPP Film Capacitors

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요 약 : 이축연신 폴리프로필렌으로 만들어진 고전압용 capacitor에서 넓은 면적의 전극을 erosion 시켜 capacitor의 capacitance값을 저하시키는 요인으로 작용하는 grape-cluster를 실험실에서 재현할 수 있는 장치를 고안하였으며, 이를 이용하여 BOPP 필름에 grape-cluster를 발생시킨 후 현미경 관찰을 통하여 grape-clustering process의 원인 및 과정을 연구하였다. 연구결과, grape-cluster는 불완전한 clearing에 의하여 발생되어 넓은 면적의 전극을 erosion시키는 현상이라는 것이 밝혀 졌다. 또한 microgap에서 발생하는 부분방전에 의하여 BOPP 필름에서 국부적인 절연파괴가 일어나는데, 이때 수반된 에너지가 완전하게 clearing되지 못하는 경우 BOPP 필름표면에 극심한 손상을 입혀, 이 손상부위에서 다시 전기집중현상에 의한 국부적인 절연파괴가 일어난다. 이들의 연속적인 현상에 의하여 grape-cluster가 발생하는 것으로 밝혀졌다.

Abstract : Grape-clusters responsible for an unacceptable capacitance loss in BOPP (Biaxially Oriented Polypropylene) roll capacitors were reproduced in a lab scale test system and then grape-clustering mechanisms were investigated by studying the damage morphology. Experimental observation indicates that the grape-cluster is not a discrete event but a sequential cascade event resulting from an unsuccessful clear which produces damages at its erosion edges. Initiation of the puncturing event may take place at weak spots such as impurities and microgaps. An extensive partial discharge may be one of the causes for the initiation. Propagation and hence a massive electrode erosion takes place by a lateral dissipation of stored electrostatic energy. A sudden release of such energy with energetic ions generated in a discharge event creates damages at its erosion edges when incompletely dissipated. Such damages result in weak spots again with an electric field enhancement and act as initiation sites for the next events.

INTRODUCTION

Metallized film capacitors, composed of biaxially oriented polypropylene (BOPP) film wrapped on a mandrel to yield a desired capacitance value, rely on ultrathin metal electrodes in order to operate at the high electrical stresses needed for an economical product. The metal is vapor deposited to a thickness on the order of 100 monolayers. Such thin metallization layer has an advantage that any defect which causes a failure will result in sufficient removal of the metal at the failure spot so that the discharge is 'cleared' and the capacitor can resume normal operation.[1~3] However, the thin metallization electrode is prone to erosion under undesired conditions, and can result in an unacceptable loss in capacitance value. A large capacitance loss is the major limitation to capacitor improvement today.

Two processes responsible for the degradation of capacitors have been identified : one is the clearing process and the other is the grape-clustering process. The clearing events appear to be isolated single events, each removing electrode material around the puncture in a localized region of negligible area compared to the overall capacitor area. Grape-clusters, the typical morphology of which is shown in Figure 1, are the main cause for such a large loss in capacitance. It appears to be a bunch of single events connected to one another which lead eventually to a broader area of electrode removal.

A significant improvement in reliability of roll capacitors has not been accomplished mainly due to two reasons : One is that the mechanisms responsible for the grape-clustering process are not exactly known and the other is that in conjunction to the first reason no efficient test methods are available so far. Previously, the only way to obtain data on the grape-clustering process has been to wind capacitors and subject to testing which continues for months to obtain a single data point. With real capacitors, also, separating each layer from a rolled capacitor is tedious and it is very difficult, from roll capacitors, to obtain clean specimen for the further study such as structural or morphological tests.

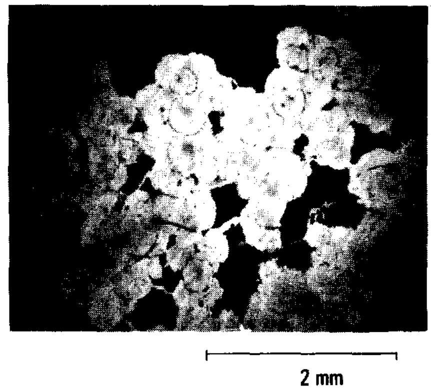

Fig. 1. Grape-cluster from the failed film capacitor : 6 μm thick BOPP film with Zn-metallization.

In this study, grape-clusters were reproduced in a lab scale test system. The morphology of damaged film capacitor was investigated to elucidate the mechanisms of the grape-clustering process.

EXPERIMENTALS

Biaxially oriented polypropylene (BOPP) films with Zn- or Al-metallization were used as samples. The thickness of these films was 6 μm. The surface resistivity of Al-metallized layer was 2.2 ohms per square and that of Zn-one was 5.7 ohms per square.

The diagram of the test chamber used in this study is shown in Figure 2. It consists of power supply to apply the voltage to the sample, the graded electrode to prevent the premature breakdown at the edge region of the electrode and the sample holder with which up to 5 films can be installed without wrinkling. The whole test set was installed in a vacuum chamber through which the gas environment can be controlled. The center electrode was surrounded by nine equally spaced copper rings tied to one another by 10 M ohm resisters. The last ring is connected to the ground through a 100 M ohm resistor. This configuration can pre-

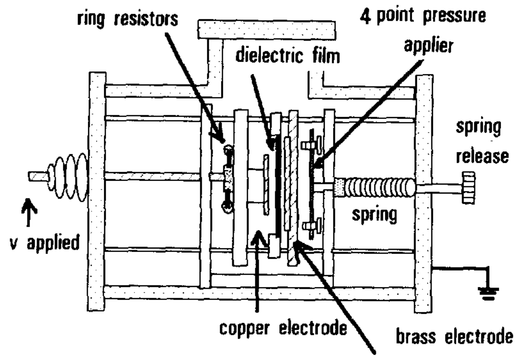

Fig. 2. Diagram of test system for generating lab grape-cluster.

vent the premature breakdown of the test dielectrics along the edge of the center electrode.

A buffer layer made of two 8 μm thick plain BOPP was used mainly to prevent the mechanical damage, causing incorrect test conditions, on the sample surface by the spring-tight. With this geometry, problems due to uneven squeeze of test films were expected to be diminished.

Experiments to obtain grape-clusters were carried out in the following way. After the film was set up in the test cell, the capacitance between two electrodes was measured. External voltage was ramped up to the voltage where the first discharge was detected by a current pulse. Then the voltage was maintained at that level in order to prevent the permanent dielectric breakdown of the test film. If the average current exceeded 300 μA without any current pulses, the film was considered to be dielectrically failed and the voltage was recorded as a dielectric breakdown voltage. Then samples which did not show permanent dielectric failure were subjected to the testing for the damage morphology using optical and scanning electron microscopes.

The lab air was charged into the chamber following a successive two or three evacuating-purging sequence to ensure only lab air is filled. Test film was spring-tightened prior to charging the gas so that the gas diffuses into the microgaps present between the films.

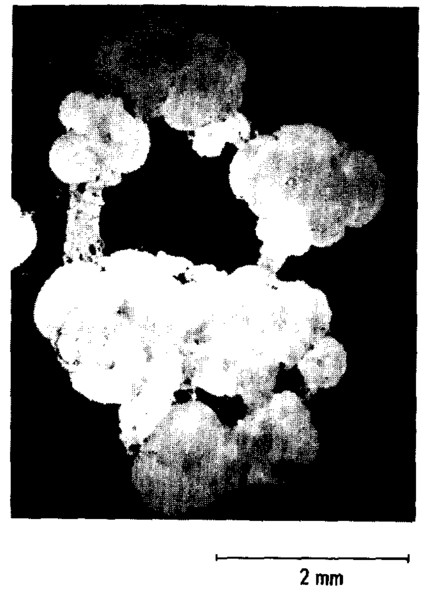

Fig. 3. Grape-cluster from lab test system : 6 μm thick BOPP film with Zn-metallization, 5.77 ohm/square, lab air, 700 V_{rms}.

RESULTS AND DISCUSSION

Lab Grape-clusters

A typical morphology of electrode erosion obtained from a lab scale acceleration tests is shown in Figure 3. The voltage applied was 700 V_{rms} in a lab air condition and the sample was the Zn-metallized BOPP film. A large area of electrode erosion resulted from the application of ac stress. Each circular area (single event) has a puncture at the center and irregular shaped erosion around the puncture the average size of which is approximately 0.7 mm in this particular case. Also, many interchannels between each single event were observed.

Lab grape-clusters (Figure 3) have every feature found in failed roll capacitors (Figure 1). The major difference is the size of single events, possibly due to the difference in the voltage levels between two experiments.

Grape-clustering Process

In order to identify the grape-clustering sequence, samples were taken from the test chamber af-

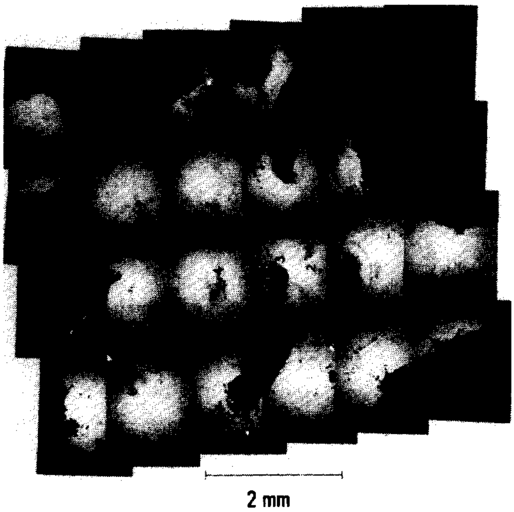

Fig. 4. Lab grape-cluster showing a large area of electrode erosion : 6 μm thick BOPP film with Al-metallization, 2.2 ohm/square, lab air, 3.8 kV_{dc}.

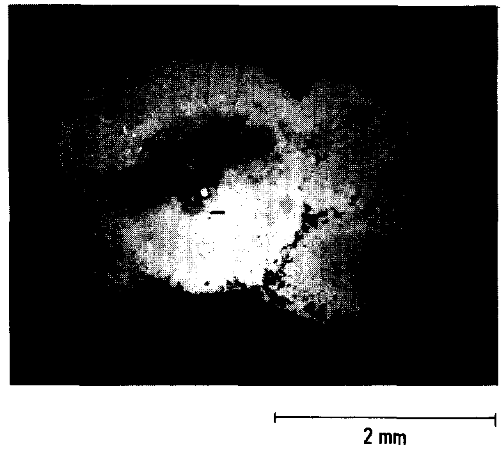

Fig. 5. Electrode erosion after a series of current pulses : 6 μm thick BOPP film with All-metallization, 2.2 ohm/square, lab air, 700 V_{rms}.

ter several current pulses were detected. This test was done under dc voltages. A typical lab grape-cluster showing a large area of electrode erosion is shown in Figure 4. In this figure one can notice that most events have a severely damaged spot near the puncture, blasting either radially or towards only one direction. Circular erosion #1 has a puncture at its center and another puncture at its perimeter. After this, one fan-shaped erosion is found, which is followed by an electrode erosion with the puncture #3. Two streams of the consecutive electrode erosion resulting in a massive electrode erosion are identifiable : one grows from #1 to #6 (#1→#2→#3→#4→#5→#6) and the other from #1 to #9 (#1→#2→#3→#7→#8→#9). From this figure it can be seen that most punctures except the one marked by #1 are developed mostly at the edge of perimeter erosion and that a large area of electrode erosion is resulted from many fan-shaped erosions.

Regarding the sequence of electrode erosion, Figure 5 is more informative. The specimen for this picture was taken out of the test chamber after a series of current pulses at 3~4 kV_{dc}. A circular erosion marked by #1 has three perimeter erosions. At the edge of erosion #2, another puncture having a fan-shaped perimeter expansion is observed.

With the assistance of the result shown in Figure 5, it may be reasonable to conclude that the large area of electrode erosion in Figure 4 was caused by the circular erosion marked by #1 and propagated into a large area by the rest of events marked #2 to #9.

At this stage, it is somewhat clear that grape-clusters grow into a large area by a sequential event of puncturing and perimeter erosion. The expansion of eroded area appears to continue until an additional energy made more erosion. This sequential process will be ended up with a grape-cluster of a large area. It can be also easily speculated that the grape-cluster will grow until all energy is dissipated or the dielectric is failed by a vertical dispense of energy.

Damage of Polymer Surface

The samples tested under ac stresses were subjected to a close examination using the SEM with an EDX accessory. Both metallization and polymer surfaces were examined. This study was aimed to find the clue for the causes of the successive puncturing events.

Polymer Side : Damage morphology produced by a discharge event is in Figure 6. Test films with the Al-metallization under ac voltages show some haziness at the polymer surface. Under the SEM, as shown in Figure 7, it has been proved that a bunch of mechanical pits are on the order of sub-micron. Mechanical pits were found all over the polymer surface of all samples regardless of the type of metallization.

Generally three regions on the polymer side were identified :

(1) puncture site,

(2) severely damaged region, and

(3) remote region.

These are schematically shown in Figure 8, along with those for the metallization side. The puncture is obviously a big damage which removes certain amount of polymeric material. Throughout many tests, it has been found that the shape of puncture leading to the grape-cluster shows a irregular shaped erosion whereas that leading to the clearing event shows a regularily shaped (circular) erosion. Around the puncture site, there is a severely damaged region extended to some distance which was observed to depend on the type of metallization. This damage looks like the melting of the polymer surface. Lots of mechanical pits were around. The average size of such damages around the puncture site are different depending on the type of metallization. They are about 50 and 300 μm in diameter for Al and Zn, respectively. The remote region outside a severely damaged region is believed to be apparently not damaged, but has a lot of mechanical pits of an order of submicron in diameter.

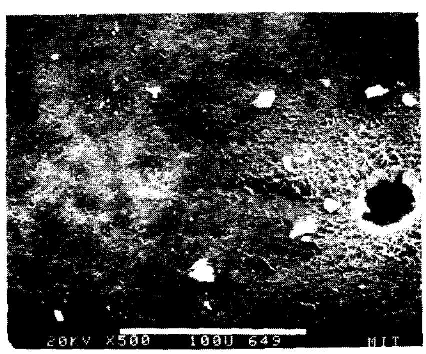

Fig. 6. Damage morphology at the polymer side.

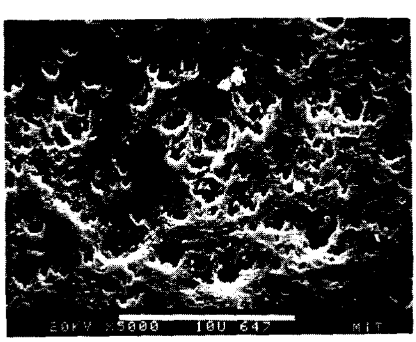

Fig. 7. Enlarged picture at the remote region.

Metallization Side : Damage morphologies at the metallization side are shown in Figure 9 and 10 for the Zn-metallization. Damage morphology under ac voltages is almost the same for all types of metallization.

Generally the damaged area of the metallization side is classified into four regions :

(1) the puncture site,

(2) severely damaged region,

(3) remote region, and

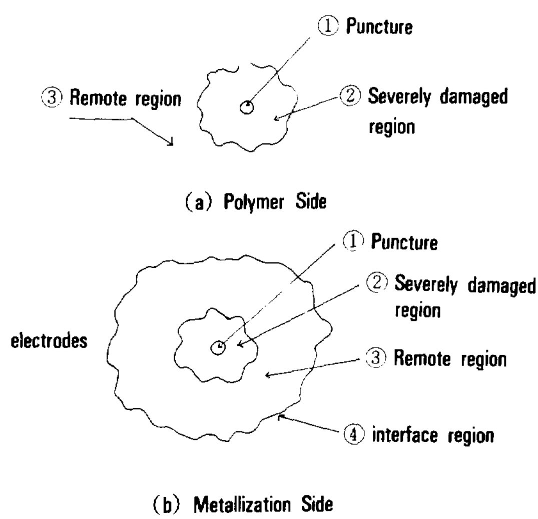

Fig. 8. Schematic representation of damaged area.

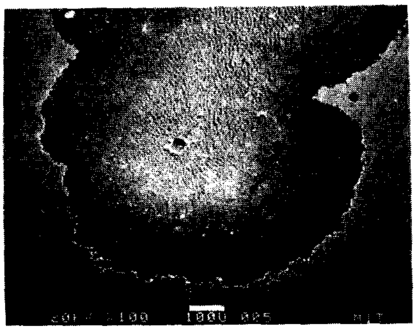

Fig. 9. Damage morphology at the metallization side.

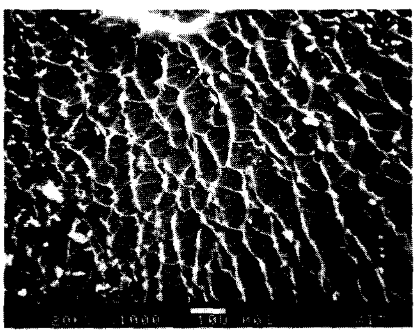

Fig. 10. Enlarged picture near the puncture.

(4) interfaces with the electrode.

A schematic representation for these regions is in Figure 8. The puncture is, as mentioned, a physical removal of the base polymer. The size of puncture seems to be almost the same, roughly 30 μm in diameter, for all metallizations. There is a severely damaged region the size and shape of which also depend on the type of metallization. Figure 10 shows that the damage in this region was propagated radially to a long distance up to a few hundred μm. Separate tests with the Zn-metallization yielded the same type of damage with a little smaller size (250 and 400 μm for the Zn and Al-metallizations, respectively). The remote area is the region between the edge of the severely damaged area and interface with the electrode. In this region, the metallization is removed as a result of the clearing activity. However, there seems to be no extensive damages on the base polymer. The interface region is of particular interest in the grape-clustering process, because it can provide other puncture sites by the buildup of the high electric field. The grape-clustering process arising from this region has been already mentioned in the previous section. There are sharp edges around the interface region.

The microscopic examination indicates that the base polymer experiences a considerable mechanical damage by the discharging events. The damage at the interface region is of particular interest in the successive puncturing events. A sudden release of energetic ions generated by the discharging event may impose a great damage at the perimeter region. As already mentioned, this type of damage is not a long-term structural change but a physical removal of certain amount of base polymer. Such removal may form weak spots in film layers. These damage may act again as the initiation point for the next event by an electric field enhancement. Punctures observed at the perimeter region can support this concept. Therfore, it can be concluded that an unsuccessful clearing event which produces a severe damage at the perimeter region is the major cause for the successive puncturing events.

Before the first event, the partial discharge seems to occur all over the polymer surface, which was confirmed by the observation hazy damages all over the polymer surface.[4~6] Under the SEM, hazy damage was found to be a lot of mechanical pits, a physical removal of the polymer substrate, the average size of which is on the order of submicron. Mechanical pits by the partial discharge at the polymer surface may lead to a premature puncture by weakening the local area of polymer substrate. The existance of an extensive partial discharge suggests that the microgaps exist between the film layers. Otherwise, the partial discharge will not occur. The existance of microgaps were confirmed by a separate study in which it was found that the different gases produce the different erosion patterns. This will be reported later.

Average electrical stresses on the order of 100 volts/μm are typical throughout the work. Higher electric stress may exist at microgaps and much higher values still exist near electrode edges. Such high fields can cause gas ionization, promote oxidation, or enhance conduction in the film. As a result a local transfer of energy will occur and accumulated damage can take place at sites where there is an opportunity for these processes. The study on the possibility of the degradation of base polymer is in progress. Preliminary results suggest that the autocatalytic oxidation takes place at the polymer surface. This is also to be reported later.

CONCLUSIONS

Grape-clusters frequently found in roll capacitors showing unacceptable capacitance losses were reproduced successfully in a lab scale test system within a short period of time, typically in an hour. Grape-cluster is a sequential cascade event resulting from an unsuccessful clear which produces severe damages at erosion edges. Initiation of the puncturing event may take place at weak spots such as impurities and microgaps. Propagation and hence a massive electrode erosion takes place by a lateral dissipation of the stored electrostatic energy. A sudden release of such energy with energetic ions generated in a discharge event creates damages at its erosion edges when incompletely dissipated. Damages at erosion edges are weak spots resulting in an electric field enhancement and act as initiation sites for the next events.

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