The Characteristics and Growth Mechanisms of Demetallization due to Self Healing on MPPF for Capacitor Applications

Jong-Wook Jung* and Hee-Ro Kwak**

Abstract - In order to help understand the growth mechanisms of demetallization due to self healing on a metallized polypropylene film (MPPF), several types of defects affecting the breakdown of capacitor dielectrics were made. The breakdown voltages with dielectric thickness were measured at self healing and the demetallized area was evaluated for all of the self healing events. The shapes and growth processes of the demetallized spots on the dielectrics were investigated. As a result, self healing mainly occurred at pin tips, wrinkle sides, and junctions of the wrinkles, and the breakdown voltages strongly depended on the thickness of the dielectrics. In addition, the demetallized area due to self healing was governed by the breakdown voltage and it has been mainly grown by some factors; the applied voltage; the consequent self healing events taking place at the circumference of the original self healing spots; the conductive paths formed by two or more self healing spots and by the consequent self healing spots.

Keywords: consequent self healing, demetallization, metallized polypropylene film (MPPF), self healing

1. Introduction

Capacitors have been widely employed for industrial applications. In the case of a capacitor that employs a metallized polymer film such as a dielectric, the electrical characteristics have been remarkably improved by self healing. The terminology of "self healing" implies the automatic insulation recovering phenomenon occurring on a very thin metallized film, and was first used by Klein [1-3]. With the advance of polymer technology, self healing has greatly contributed to raising the energy density and the reliability of the capacitors.

Fig. 1 shows the self healing spot and its process.

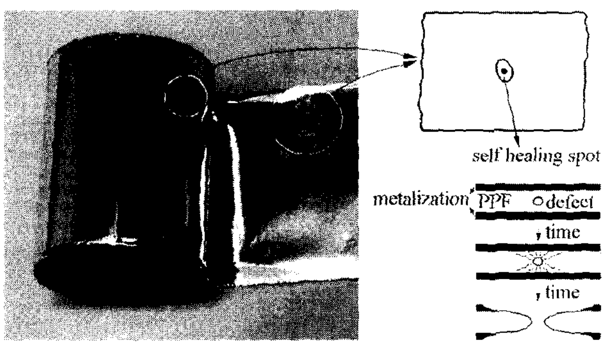

Fig. 1 *Self healing spot and its creation process*

As shown in Fig. 1, when a defect exists in a dielectric, electrical breakdown takes place at the point of defect as the voltage applied to the dielectric increases. A very small hole is created at the self healed spot, and the deposited metal electrode around the hole is evaporated. The demetallized area on the polymer film is electrically isolated like a melted fuse, therefore short circuit current can be cut out. Thus, the dielectric can recover its insulation through the self healing process. Up to now, most studies on self healing have been mainly focused on the gas generated at self healing, the factors affecting self healing, or the dielectric strength characteristics of the metallized polymer films [1, 4-8]. However, the self healing characteristics depending on the defect shapes or the studies on the self healing locations have scarcely been reported. The defects consist of various modes such as a wrinkle or void created in the winding and impregnating processes [4-9].

In this paper, PPF thickness and several types of defects that may be created in the capacitor manufacturing process due to unbalanced winding tension were selected as experimental parameters, and the self healing characteristics were compared and analyzed in each defect case.

2. Experimental

2.1 Experimental Setup

Fig. 2 illustrates the experimental setup to understand the self healing characteristics of the MPPF with several shapes of voids under a.c condition.

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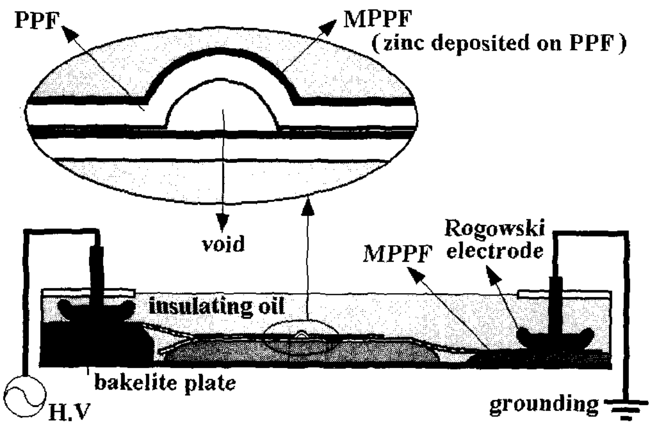


Fig. 2 Experimental setup

As illustrated in Fig. 2, void defects were made between the two MPPFs. The high voltage generator (Hypotronics model: 750-5CF), which could apply up to 50 kV_{ac} was connected to one MPPF through a Rogowski electrode. The other MPPF was grounded. A high voltage probe (Pulse Electronic Engineering model: EP-50K) was used to measure the applied voltage.

The surface resistance of the metallization is generally determined by 3~9 Ω , and it plays an important role in oxidizing and burning out the metallization at self healing. A higher resistance of metallization can be more effective from the viewpoint of the insulation ability of the demetallized area, because the higher the metallization resistance is, the broader the demetallized area becomes. However, the capacitance is becoming reduced by self healing, worsening the performance of the capacitor [4-9].

Table 1 shows the specification of the MPPF used in this experiment.

Table 1 Specification of MPPF

PPF thickness	metal / thickness	surface resistance
5, 6, 10, 12 μm	Zn / 300 Å	7 Ω

Insulating oil (SUN OHM C) was used as an impregnant. The impregnant can be contaminated by the metallic oxide and the hydrocarbon gas generated at self healing, which reduces the insulating performance of the impregnant [1]. Therefore, the impregnant was renewed every time the MPPF was changed. Table 2 shows the electrical and physical properties of the insulating oil.

Table 2 Electrical and physical properties of insulating oil

specific weight	viscosity (cSt)	ε '	tanδ	dielectric strength (kV/2.5 mm)
0.916	12.3	2.8	0.03	72

To measure the currents at self healing, a CT was installed at the grounding conductor, and it was connected to the input terminal of an oscilloscope.

2.2 Experimental Procedure

The MPPFs of 5, 6, 10 and 12 μm in thickness were sheared by 6× 15 cm. Each of them was laminated by two sheets on the bakelite plate and then impregnated with the insulating oil. After applying a.c voltage at the rate of 0.5 kV/s by using a high voltage generator, PD characteristics, applied voltages, demetallized area and currents in the grounding conductor at self healing were investigated and measured. Some of the self healing events were recorded. This procedure was repeated every time the MPPFs were changed, thus about 60 self healing data for each PPF thickness were acquired.

3. Results and Discussion

3.1 Self Healing of MPPF

The self healing spots on the MPPF were taken by a digital camera (Kodak model: DC-290, resolution ability: 1548× 1032).

Fig. 3 shows the typical demetallized spot on the MPPF due to self healing.

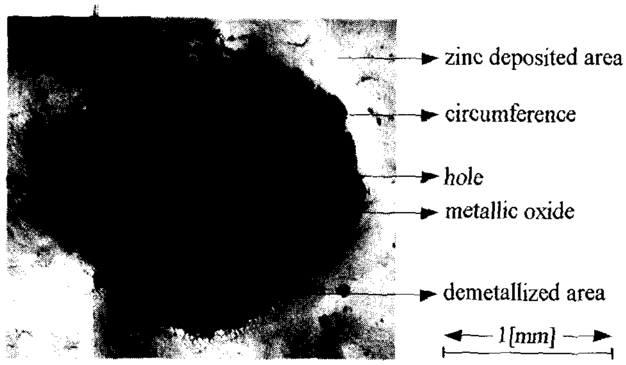


Fig. 3 Demetallized spot created by self healing(12 μm, 3 kV_{ac})

As illustrated in Fig. 3, a very small hole was created at the center of the demetallized spot, and the metallization around the hole was evaporated. The circumference of the demetallized area was indented with coarse burrs, and fractions of metal oxide due to self healing were scattered in the demetallized area. It is well known that the metal oxide is Al_2O_3 insulator or ZnO semiconductor depending on what metal is deposited on the PPF [4-9]. In this experiment, it was also observed that there was a slight voltage drop at self healing.

3.2 PD Characteristics of MPPF

When a.c voltage was applied to the MPPF, PD was observed at a much lower voltage than the breakdown voltage of a PPF, and in some cases, noise was emitted and the demetallized area was expanded. Partial discharge inception voltages (PDIVs) mostly increased by the pre-self healing events that began to take place at the weakest point on the MPPF prior to the main self healing events. It is considered that the weakest point due to defects is first removed by pre-self healing. In this case, PDIV was regardless of PPF thickness, and it tended to increase up to the main self healing voltage after several weak points had been completely removed by pre self healing.

3.3 Main Self Healing Voltage by PPF Thickness

The breakdown voltages of the PPFs have been somewhat differently reported depending on the experimental condition and the various factors; the PPF manufacturing type; the film stretching and its surface treatment, etc. However, about 0.2~0.4 $kV_{ac}/\mu m$ are usually considered the breakdown withstand strength of the PPF itself.

Fig. 4 shows the main self healing voltage by PPF thickness, which is similar to previous works [5-9].

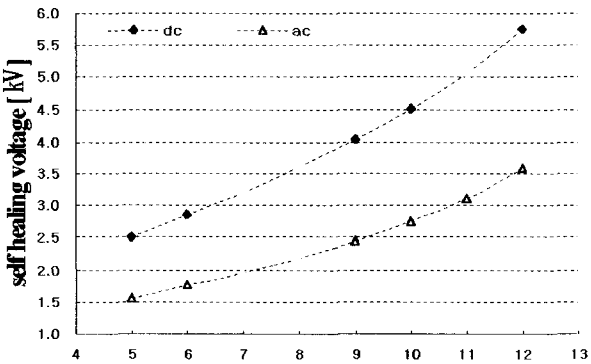


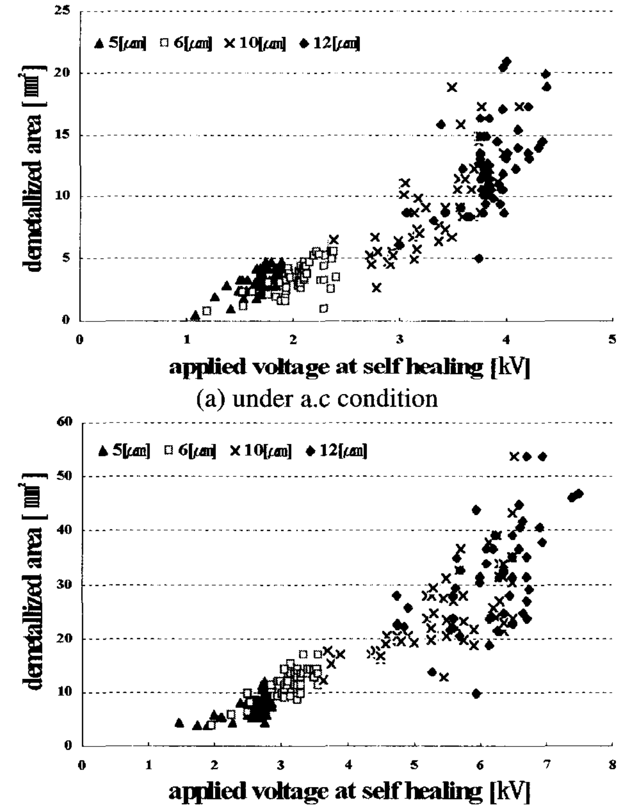
Fig. 4 Main self healing voltage by PPF thickness

As shown in Fig. 4, the main self healing voltage increased at the rate of about 0.23 $kV_{ac}/\mu m$ with PPF thickness.

3.4 Demetallized Area due to Self Healing on MPPF

Fig. 5 shows the demetallized area due to self healing on the MPPF.

As shown in Fig. 5, when voltage was applied, the demetallized area due to self healing was broadening with the applied voltage. This is considered because the applied voltage at self healing increased with PPF thickness. Also, the demetallized area was somewhat different even though the applied voltage was almost identical. This is assumed because the MPPF thickness cannot be entirely the same all over the MPPF area, which makes the surface resistance of metallized PPF slightly different.



(a) under a.c condition

(b) under d.c condition

Fig. 5 Demetallized area due to self healing on MPPF by applied voltage and PPF thickness

3.5 Discharge Current at Self Healing

Fig. 6 shows the peak discharge current measured in the grounding conductor at self healing.

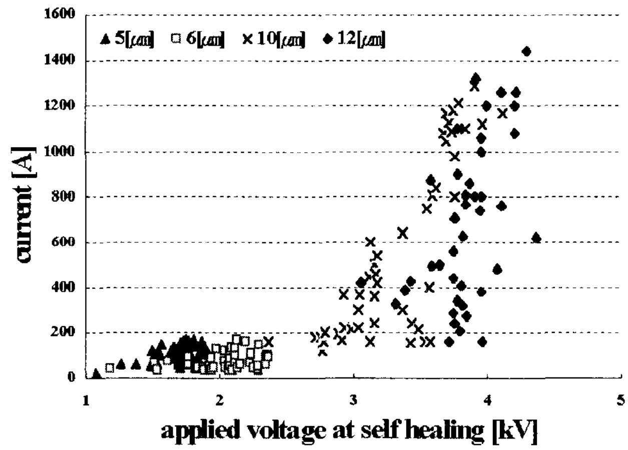
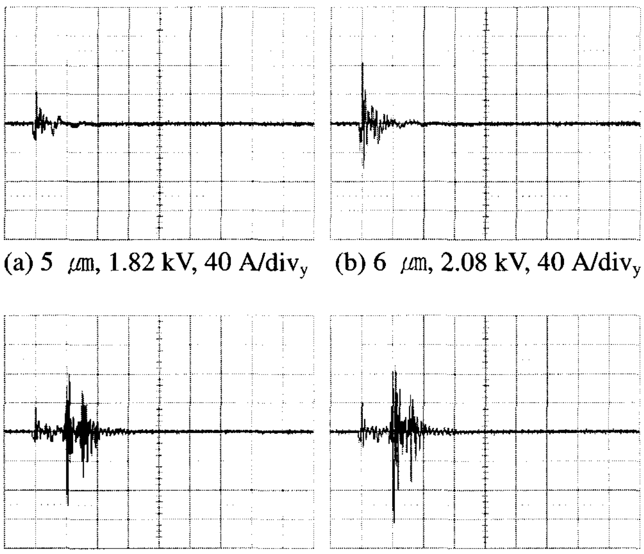


Fig. 6 Discharge current at self healing

As shown in Fig. 6, the peak discharge current in the grounding conductor increased, as a whole, with the applied voltage at self healing. In the case of 10 and 12 μm PPFs, most of the peak currents were widely varied, and they considerably increased compared to the PPFs of 5 and

6 ㎛ thickness. In the case of 5 and 6 ㎛ PPFs, each self healing occurred at different spots, while it was frequently observed that, in the case of 10 and 12 ㎛ PPFs, the demetallized area was overlapped by consequent self healing occurring near the first self healing spot. Therefore, in the case of the first self healing event, the current which radially flows from the punctured point evaporates the metallization, while in the case of consequent self healing occurring near the first self healing, the current hardly flows in the previously demetallized area but rather through the metallized area. Therefore, it can be assumed that the peak discharge current at the first self healing is far different from that at consequent self healing and it is also considered that the peak current range of 10 and 12 ㎛ PPFs is wider than that of 5, 6 ㎛ PPFs.

Fig. 7 shows the typical waveforms of the current in the grounding conductor at self healing, by PPF thickness.



(a) 5 ㎛, 1.82 kV, 40 A/div$_y$ (b) 6 ㎛, 2.08 kV, 40 A/div$_y$

(c) 10 ㎛, 3.16 kV, 200 A/div$_y$ (d) 12 ㎛, 3.82 kV, 200 A/div$_y$

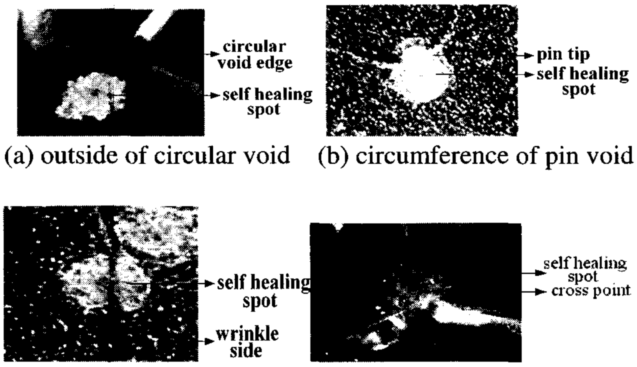
Fig. 7 Current waveforms at self healing (1 μs/div$_x$)

As depicted in Fig. 7, when a.c voltage was applied to the MPPF, the current in the grounding conductor was oscillated and damped, and mostly tended to be zero within 3 μs. In particular, the current peaks were somewhat delayed in the case of 10 and 12 ㎛ PPFs. Also, the peak current in the grounding conductor increased with the applied voltage at self healing.

3.6 Effect of Defect Shapes on Self Healing

In this experiment, void defects with several shapes were made to investigate the effect of the void defects between two MPPFs on self healing. When a.c voltage was applied to the MPPF, all the self healing events were observed.

Fig. 8 shows the self healing spots taken, and Table 3 shows the self healing characteristics by the defect shapes.

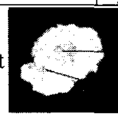
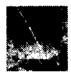


(a) outside of circular void (b) circumference of pin void

(c) side of wrinkle (d) X/Y junction

Fig. 8 Self healing spots

Table 3 Self healing (S.H) characteristics by defect shapes

	circular void	pin void	wrinkle	X/Y junction
S.H event probability	very low	high	high	high
S.H location	· circumferences	· tips	· tips · sides	· tips · sides · junction
feature	· Consequent self healing at the circumference of demetallized spot due to self healing observed  · gas generated at self healing → dissapeared when voltage applied and increased			
void shape				

· pin void : void equal or less than 1 cm in length
· wrinkle : void more than 1 cm in length
· X/Y junction : wrinkle with cross points

As shown in Table 3, when a.c voltage was applied to the MPPF with defects, self healing mainly occurred at pin tips of a pin void, wrinkle tips and sides of the wrinkle, and its tips, sides and cross points of an X/Y junction of wrinkles. In addition, as shown in Fig. 8(a), self healing at a circular void hardly occurred. Even though self healing transpired at the circular void, the self healing spots were limited to its circumference. In the case that self healing took place at the circumference of the circular void, the air in the circular void was released into the impregnant and two laminated sheets of the MPPF were attracted to each other by the electrostatic force as soon as self healing occurred. Moreover, when the voids experienced voltage stress, their diameter was reduced in all cases. In some cases, however, the void slowly moved between two sheets of the MPPF without any regularity, and it was ultimately slipped out into the impregnant. It was sometimes observed that the voids vibrated at one position without moving here and there. As a result, it was verified that the self healing events mainly took place at the tips and sides of the void defects.

3.7 Creation and Growth of Self Healing

As seen in the figure in Table 3, the consequent self healing events were frequently observed on the circumference of the demetallized area after self healing. This is considered as a process of the self healing mechanism.

Fig. 9 illustrates the types of self healing and their growth mechanism.

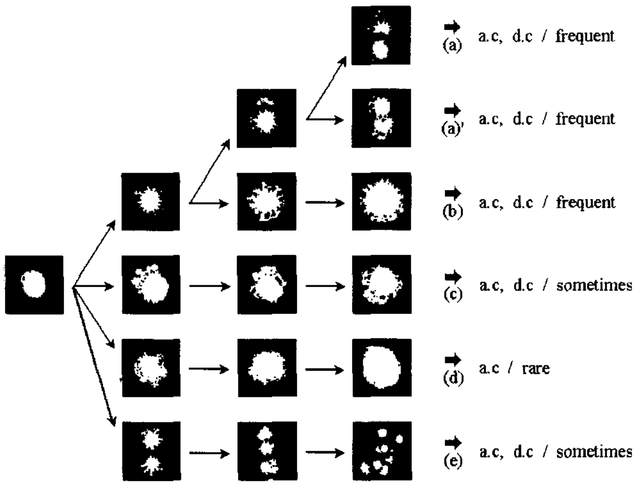


Fig. 9 Consequent self healing occurring after self healing and its growth mechanism

As illustrated in Fig. 9, the circumference of the demetallized spots created just after self healing curved coarsely. A leakage current path was formed with voltage applied time between and the circumference and the hole centered in the demetallized spot. A fine surface tracking occurs along the path, and the conductive path was grown with voltage applied time. For the reason mentioned, the demetallized area on the MPPF was radially spread out to take on a frost shape (Fig. 9(a), (b)). The electric field was concentrated on the tips of the frost-shaped demetallized spot to be weak points. Thus, the consequent self healing event took place on the weak points and its demetallized area was expanded as shown in Fig. 9(a) and 9(a), or the tips of the frost-shaped demetallized spot were inter-bridged and expanded to gradually reduce the metal deposited area as shown in Fig. 9(b), and 9(c) shows the case in which the leakage of currents is partially concentrated on several points of the circumference and a few cloud-shaped pieces appear on the circumference. Fig. 9(d) rarely appears and then only at a.c low voltages and it also shapes cumuli. This shape is also caused by the partial concentration of the electric field, similar to Fig. 9(a) and 9(b). Its demetallized area, however, tended to be expanded all over the circumference of the demetallized area, which is different from the other cases. Fig. 9(e) shows the bridge-shaped demetallization, which hardly occurred when compared to Fig. 9(a) and 9(b). It is commonly observed with noise in the case that the applied voltage increased near the critical breakdown voltage of the PPF after several self healing events. In this case, the demetallized area can be expanded by the bridge formed between two or more self healing spots. In addition, even if there is not entire demetallization, the inner area surrounded by the bridge lines is electrically isolated, therefore the capacitance loss could increase much more.

In the case of Fig. 9(a) and 9(b), the frost tips under d.c condition were larger than those under a.c condition. Considering that the demetallized area was hardly spread out at low voltages and shaped like as in Fig. 9(d), it is considered because the d.c. applied voltage was greater than a.c applied voltage at self healing.

4. Conclusions

After observing the self healing spots on the MPPF with several shapes of the void defect, the self healing characteristics were compared and analyzed.

As a result, this paper concludes as follows;

(1) PDs were generally observed at relatively low voltage, and the PDIVs tended to increase with the number of pre-self healing due to void defects.
(2) The main self healing voltage increased with PPF thickness.
(3) The demetallized area at self healing on the MPPF roughly increased with the applied voltage at self healing.
(4) The peak discharge current in the grounding conductor at self healing increased with the applied voltage, and it was oscillated and damped.
(5) Self healing mainly took place at; pin tips of a pin void; tips and sides of the wrinkle; and tips, sides and X/Y junction of wrinkles. Self healing at a circular void hardly occurred. Even though self healing occurred at the circular void, the demetallized spots were limited to its circumference.
(6) Consequent self healing took place at the circumference of the demetallized area.

Various factors such as metallization resistance, metallization thickness and the viscosity of the impregnant, etc., besides the parameters used in this paper, affect the self healing characteristics. In this paper, only the defects occurring in manufacturing were taken into account to analyze the self healing characteristics of the MPPF, and the experimental results were compared. In the future, further study using the simulations such as electric field analysis on self healing must be carried out to more various factors.

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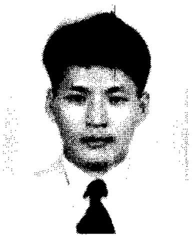

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