Mechanical Stress Distribution inside Dry Capacitor Elements

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Abstract

Many power products are produced by winding paper, polymer film or metal foils around an electrically active or passive core, like cables, bushings and capacitor elements. The mechanical stress distribution inside the product has high impact on its final performance. The stress distribution will be determined by the selected materials, winding parameters, and the ambient temperature. In this work the stress distribution inside dry metallized film capacitor elements for HV applications has been investigated using multiple experimental methods: Parotester, Smith needle, Pressure sensors and X-ray computed tomography. The results showed that the tested methods were unable to provide exact values of the radial stress distribution inside the capacitor element. As a continuation, the nonlinear material properties of the biaxially oriented polypropylene capacitor film were characterized. This work indicated that the temperature and the initial film stress will have an effect on the resulting tightness of the capacitor element.

1. Introduction

Winding is a production method that was first used in the early 1800s, when paper and textile could be produced continuously. Today, it is used when producing different types of power products, like cables, bushings and capacitor elements. One of the drawbacks with winding power products is that voids are created inside the products between film layers. Voids are hard to avoid due to the surface structure of the used materials. It is well known that voids can lead to partial discharges in HV products, which will damage the insulation material. In order to remove voids many HV products are therefore impregnated with either oil or thermoset resin. Dry metalized film capacitors (DMFC) are one of the few HV products which are rarely impregnated.

The quality and safety of a DMFC is affects by the self-healing performance of the capacitor film [1]. Self-healing is in turn greatly influenced by the interlayer pressure in the DMFC element. Interlayer air present between the capacitor films will also influence self-healing. In DC applications the ionization of interlayer air will affect the duration of the self-healing process and increase the self-healing area [1]. Under AC conditions however, the air can lead to electrochemical corrosion of the metallization layer effecting the lifetime of the element [1]. Different methods are today used in order to increase the tightness of capacitor elements, and thereby reducing the presence of interlayer air, such as adding a cover film, using a vacuum process and a heat treatment.

Biaxially oriented polypropylene (BOPP) film is used in a majority of DMFC for HV power applications. BOPP has high breakdown strength, low dissipation factor and good self-healing capability [2]. BOPP film used for DMFC elements is mainly produced through a sequential biaxial stretching process. The film is stretched in two directions at elevated temperatures below the melting point of the material [3]. This process results in a highly oriented morphology. The BOPP film contains both a highly oriented crystalline phase and an oriented amorphous phase [4]. This affects the behavior of the capacitor film when exposed to elevated temperatures, like heat treatment of capacitor elements or exposure to high ambient temperature. The oriented amorphous phase wants to contract and relax. This results in shrinkage of the film, which increases the tightness of the capacitor element [1]. In order to produce capacitor elements with improved performance, understanding the correlation between the stress distributions in newly produced elements vs. thermally treated elements is of high importance.

The aim of this work was to identify an experimental method that could be used to measure the stress distribution in capacitor elements before and after thermal treatments. The following methods were tried: Parotester, Smith needle, Pressure sensors and X-ray computed tomography. The nonlinear material properties of the BOPP film were also characterized. The relaxation behavior in the machine direction of the film under tensile stress was investigated at multiple temperatures. These experiments showed that both the temperature and the initial stress will have an effect on the resulting properties of the capacitor element. The experimental results were used as inputs to a constitutive model for mechanical simulations, which will be used to produce optimized capacitor elements.

2. Experimental

2.1 Materials

A standard commercially available biaxially oriented PP capacitor film produced on a tenter production line with sequential drawing was used for these experiments. The film was 6 µm thick. Winding cores of different dimensions and materials (PP, glass fiber reinforced polybutylene terephthalate (PBT), and aluminum) were used. The capacitor elements were wound on commercially available winding machines.

2.2 Parotester & Smith Needle

These two measuring techniques are used within the paper industry to measure the tightness of paper rolls.

The Parotester is a dynamic hardness test. The test compares impact and rebound speed of a metal test tip. The loss of kinetic energy is converted into a hardness value of unit LU. A Parotester2 was used in this experiment, see Figure 1a.

The Smith needle tester or Smith Roll Tightness Tester measures interlayer pressure. It measures the force required to penetrate a spring-loaded needle to a constant depth between the layers of a roll, see Figure 1b. The test yields an arbitrary unit. In this experiment a S version was used (high roll hardness).

2.3 Pressure Sensors

FlexiForce high temperature force and load sensor model #HT201 from Tekscan was used in this experiment. These sensors were 203 µm thick and could withstand temperatures up to 200°C. Prior to use the sensors were calibrated for pressures between 0.5-15 MPa and for temperatures between 23°C and 90°C. A puck of aluminum foil (10 µm thick) needed to be placed on the sensing area in order to receive high quality readings, see Figure 2.

2.4 X-ray Computed Tomography

X-ray computed tomography can be used as a non-destructive testing method to search for voids or metallic particles inside power products. The instrument can clearly visualize air bubbles and materials of different densities. The test was performed at the hospital in Västerås, Sweden, using a GE Light Speed Ultra.

2.5 Film Relaxation

Relaxation test were performed on film stacks cut from wound capacitor elements. The stacks contained 28 layers of capacitor film. The relaxation tests were carried out in reference to ISO 6914 [5], method A. A MTS universal test machine was used and the length of the film bundles was 100 mm. The film was first stretched to the initial stress and then the crosshead was looked in position. The change in stress with time and temperature was recorded.

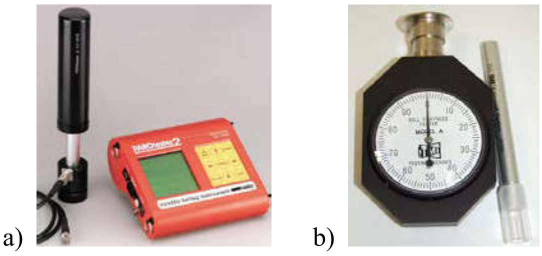

Fig. 1 – a) PAROtester 2 [6], b) Smith Needle tester [6]

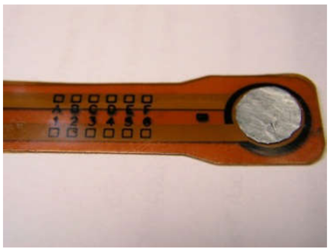

Fig. 2 - Sensor with aluminum foil puck on sensing area.

2.6 Mechanical Modeling

The modeling was performed in the finite element software Abaqus, with support from numerical calculations carried out in Matlab. A satisfactory model of the stress state was developed by modeling the PP film as a linear-elastic material and by considering the roll as a continuum.

3. Results and Discussion

3.1 Parotester & Smith Needle

The paper industry has measured the tightness of material rolls for a long time. Two commonly used methods are Parotester and Smith needle. They are both simple tests to perform. As seen in Table 1, based on multiple tests the Smith needle test showed higher accuracy on the DMFC elements compared to the Parotester. The Smith needle clearly indicated an increase in roll tightness after thermal treatment. It is also possible to see that the largest change had occurred at the outer part of the element. The Smith needle test can be used to indicate a percentage change in roll tightness, but the results are however more difficult to incorporate into mechanical models due to the arbitrary unit generated.

3.2 Pressure Sensors

Pressure sensors were incorporated during a winding session of DMFC elements. In order to minimize the change in winding parameters, the sensors were only added at two locations during natural stops in the winding process. The first location was between the winding core and metallized film and the second location was between the metallized film and the cover film (non-metallized BOPP film). The sensors showed a large difference in pressure after winding, see Figure 3. It is well known that the pressure at the outer turns is lower, resulting in higher capacitance loss in this section of the DMFC element [1]. This is also in line with the results from the Smith needle test. The pressure sensors also recorded an initial pressure relaxation taking place directly after winding, see Figure 4. This is normal for thermoplastic materials. Figure 4 also shows that a pressure drop occurred after exposing the element to an elevated temperature. This indicates that the interlayer pressure close to the sensors has decreased. The drop in pressure contradicted the results from the Smith needle

Table 1. – Results from using Parotester and Smith Needle

Measuring Location	After Winding		After Thermal Treatment	
	Parotester *[LU]*	*Smith needle* *[Smith S-Needle]*	*Parotester* *[LU]*	*Smith needle* *[Smith S-Needle]*
Close to winding core	528 ± 37	198 ± 2	-	213 ± 13
Middle	534 ± 14	176 ± 5	-	228 ± 3
Close to coverfilm	475 ± 30	153 ± 6	-	193 ± 22

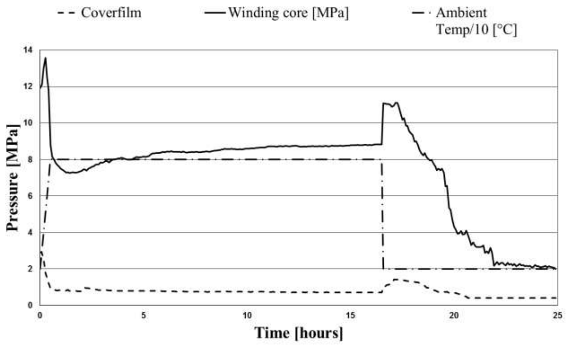

Fig. 3 – Large difference in pressure between the bobbin and the cover film. (Aluminum winding core used.)

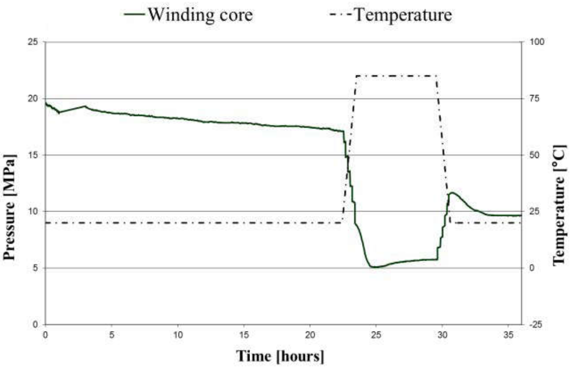

Fig. 4 – Pressure close to bobbin versus temperature indicating a large reduction after thermal treatment.

test. The pressure sensor was substantially thicker than the capacitor film (200 vs. 6 µm) which most probably caused a local relaxation of the film surrounding the sensors. As a result it is not recommended to use this type of pressure sensors, unless they have similar thickness as the used capacitor film.

3.3 X-ray Computed Tomography (CT)

The sensitivity of the instrument used was unable to record density variations due to the pressure distribution inside the element. The image in Figure 5a shows a uniform element. The measured density [HU] also showed no clear variation throughout the winding. The instrument can however be used for other investigations. Figure 5b and 5c shows that materials of different densities easily can be identified using a CT.

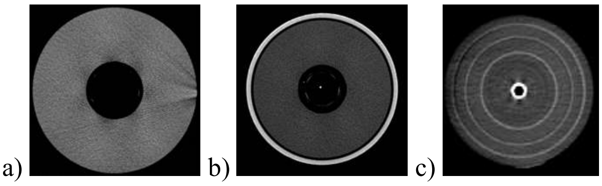

Fig. 5 – CT images of DMFC elements.
a) normal winding parameters, b) Element with housing and encapsulation, c) Element with inserted barrier film.

3.4 Film Relaxation

Film relaxation experiments were carried out in order to increase the understanding for how the mechanical properties of the BOPP film changed with temperature and time. The aim was to understand how the relaxation of the amorphous phase of the BOPP film during thermal treatments of a capacitor element will influence the resulting radial pressure in the capacitor element. Bundles of 28 layers of capacitor film were cut out from a wound capacitor element in order to enable handling of the film in the grips of the tensile machine.

The results indicated that the initial stress had a large effect on the relaxation behavior of the film. As a result, the used winding tension will influence the films relaxation behavior. Figure 6 shows that film bundles with 5 MPa initial stress behaved differently compared to tests performed with higher initial stress. After thermal treatment, the stress for the 5 MPa test nearly doubled. Due to thermal expansion, the film bundle was completely loose at the elevated temperature and as a result the polymer chains in the amorphous phase had the ability to relax and contract during the heat treatment. There was no such effect noted for the tests with higher initial stress, here the film bundles were still stretched and the polymer chains in the amorphous phase were therefore unable to contract. This indicates that the film in the capacitor element will behave differently in different sections of the element depending on the tangential stress distribution. This means that in sections with a low or negative tangential stress, the film will have the ability to shrink more compared to in sections with a high tangential stress. There is a relationship between the tangential stress and the radial stress (interlayer pressure) in cylindrical structures according to equilibrium equations. If the film shrinks in the tangential direction it will also affect the radial stress distribution in the wound element.

Figure 6 shows that the stress for the bundles with 15 MPa initial stress will after heat treatments recover to the expected extrapolated relaxed value, whereas the bundles with lower initial stress will reach a higher stress after heat treatment due to shrinkage.

In order to investigate at which temperature the relaxation of the film starts a test was performed with a stepwise increase of the temperature. Figure 7 shows that the behavior of the film changed after being heated to 55°C. It should be noted that capacitor elements may be exposed to this temperature level during normal

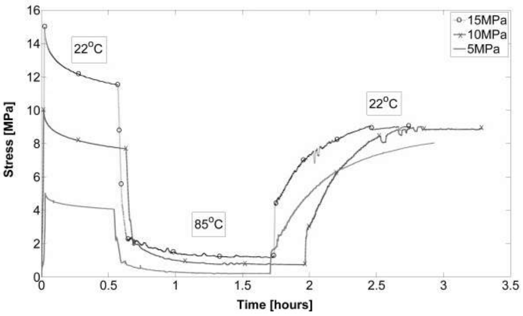

Fig. 6 – Stress relaxation curves for tests with different initial stress (5, 10, & 15 MPa)

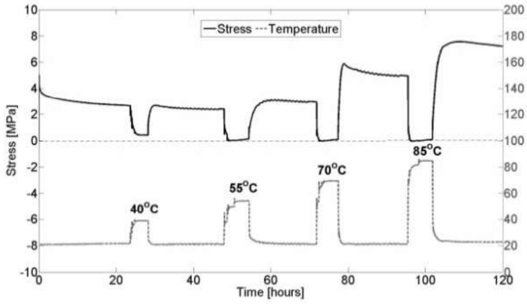

Fig. 7 – Stress relaxation with stepwise increase in temperature (5 MPa initial stress)

operation. The type of information gained in these relaxation tests are of high value, since the information can be incorporated into mechanical simulation models.

3.5 Mechanical Modeling

After relaxation testing of the BOPP film was carried out, a theoretical investigation was initiated to describe the stress state of a wound capacitor element. The BOPP film itself displays a nonlinear time-dependent behavior, which further complicates simulations of a wound element.

The generated model predicted an increase in compressive circumferential stresses in the bulk of the roll following a heat treatment. This was originated from film shrinkage occurring at the elevated temperature. Figure 8 shows the simulated stress state after temperature treatment of a DMFC element.

4. Conclusion

This work gave a valuable insight into the shrinkage and relaxation behavior of BOPP film in wound capacitor elements. The experiments indicated that the film will shrink and relax to different extent in different parts of the capacitor element, depending on the tangential stress distribution. Being able to create mechanical models instead of using experimental methods to find the pressure distribution has a clear advantage, when working towards increasing the lifetime of capacitor elements.

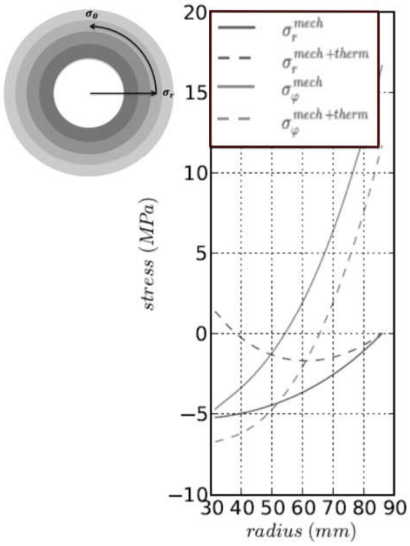

Fig. 8 – Stress state from Abaqus using cylindrical coordinates before and after thermal treatment.

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