

UV-curable Dielectrics

Metal conductors are in general coated with a dielectric coating for insulating the conductors. Such coatings require good insulating properties in a variety of environments. It is particularly important for such coatings to provide good insulating properties under extreme conditions such as in transformer coils found in power distribution. UV curable coatings are perfect candidate for dielectric coatings on metals because they are environmental friendly with no VOC; and they are fast curing, and allow high line speed production.

In this paper, a UV curable dielectric coatings for transformer coils are developed, which will possess the following properties: (a) the cured coating should be flexible so that it can withstand bending of the coated conductors; (b) It should be able to withstand immersion in oil for 28 days at 150 °C, and it should remain adherent at elevated temperature; (c) It should have a dielectric constant smaller than 5 at 60 Hz and a dielectric dissipation factor smaller than 0.05 at 25 °C, before and after hot oil exposure and smaller than 0.2 at 150 °C both at 60 Hz.

Experimental:

Coatings are made according to Table 1. The coating compositions were applied on an aluminum plate and cured with 2 J/cm² light of a fusion D bulb. For measuring the dissipation factor, 150 μm thick films were cast on a glass plate and cured with 2 J/cm; Cured coating samples were tested for flexibility and structural integrity under the strain required for a 180 degree bend of coated 0.0625" thick aluminum substrate over 0.25" mandrel at 25 °C. Visual examination of the tested samples indicated the cured samples tested maintained structural integrity and did not delaminate from the aluminum substrate. Elastic modulus (E'), viscous modulus (E''), and tan delta (E''/E') were measured by conventional DMA. A free film specimen of cured material was cut to size (about 35 mm length), measured for width and thickness and mounted. The environmental chamber containing the sample was brought to 80 °C. The sample was stretched before temperature sweep was started. The temperature was lowered in prescribed steps to the starting temperature. The temperature sweep was started and allowed to proceed upwards on the temperature scale until the material was beyond the glass transition range and well into the rubbery range. The dissipation factor was measured at 24 °C and 150° C at 60 Hz with standard equipment with stainless steel electrodes.

Results and discussions:

Aliphatic hydrocarbon urethane diacrylate is the major components in the coatings. It is synthesized by isophorone diisocyanate, a saturated hydrocarbon diol, and hydroxyethylacrylate¹. It gives the coatings hydrophobicity, flexibility and low T_g. Tricyclodecanedimethanol diacrylate is a very unique monomer. It has low viscosity, hydrophobic, good toughness and low shrinkage. It also improves the stability of the coatings in oil immersion test. Acrylated phosphoric acid is a good adhesion promoter on metals. All the coatings meet the requirement as dielectric for transformer coils.

Table 1. Coatings formula and properties

Components (wt.%)	a-formula	b-formula	c-formula	d-formula
Hydrocarbon urethane diacrylate	50	55.6	54.03	53.8
Isobornylacrylate	0	11.1	10.8	10.8
Tricyclodecanedimethanol diacrylate	24	0	0	0
2-ethylhexyl acrylate	20	0	0	0
hexandioldiacrylate	0	26.7	25.93	25.8
2-Hydroxy-2-methyl-1-phenyl-1-propanone	3.0	3.0	6.0	5.9
Phthalocyanine blue	0	0	0	0.5
Acrylated phosphoric acid	3.0	3.0	3.0	3.0
Viscosity (mPa•S)	500	785	730	730
Dissipation factor at 25 °C, 60 Hz	0.029	0.019	0.024	0.025
Dissipation factor at 150 °C, 60 Hz	0.032	0.06	0.082	0.053
Stability under 150 °C oil immersion	pass	pass	Slight defect	pass
180 ° bending test	pass	pass	pass	pass
Dielectric constant	<2.7	<2.7	<2.7	<2.7

The coatings show two glass transition temperatures indicating that the coating has two phases. One phase is the hydrocarbon which has a T_g around -10 °C. Another phase is the polyacrylate phase, which has a T_g around 50 °C. As shown in Figure 1, the concentration of photoinitiator has significant influence on the glass transition temperature of the coatings. Formula-b and formula-c use the same amount of oligomers and monomers but different amount of photoinitiator. Formula-b has 3% photoinitiator while formula-c uses 6% photoinitiator. The high photoinitiator concentration lowers the glass transition temperature. A possible reason for the depressing of T_g by high concentration of photoinitiator is due to the remaining photoinitiators in the cured coatings. The photoinitiator used in all the formulation is a liquid at room temperature. Only a very small portion of it will be consumed during the photopolymerization. When high concentration photoinitiator is used in the coatings, more free photoinitiators will remain in the cured coatings and lowers the T_g of the coatings.

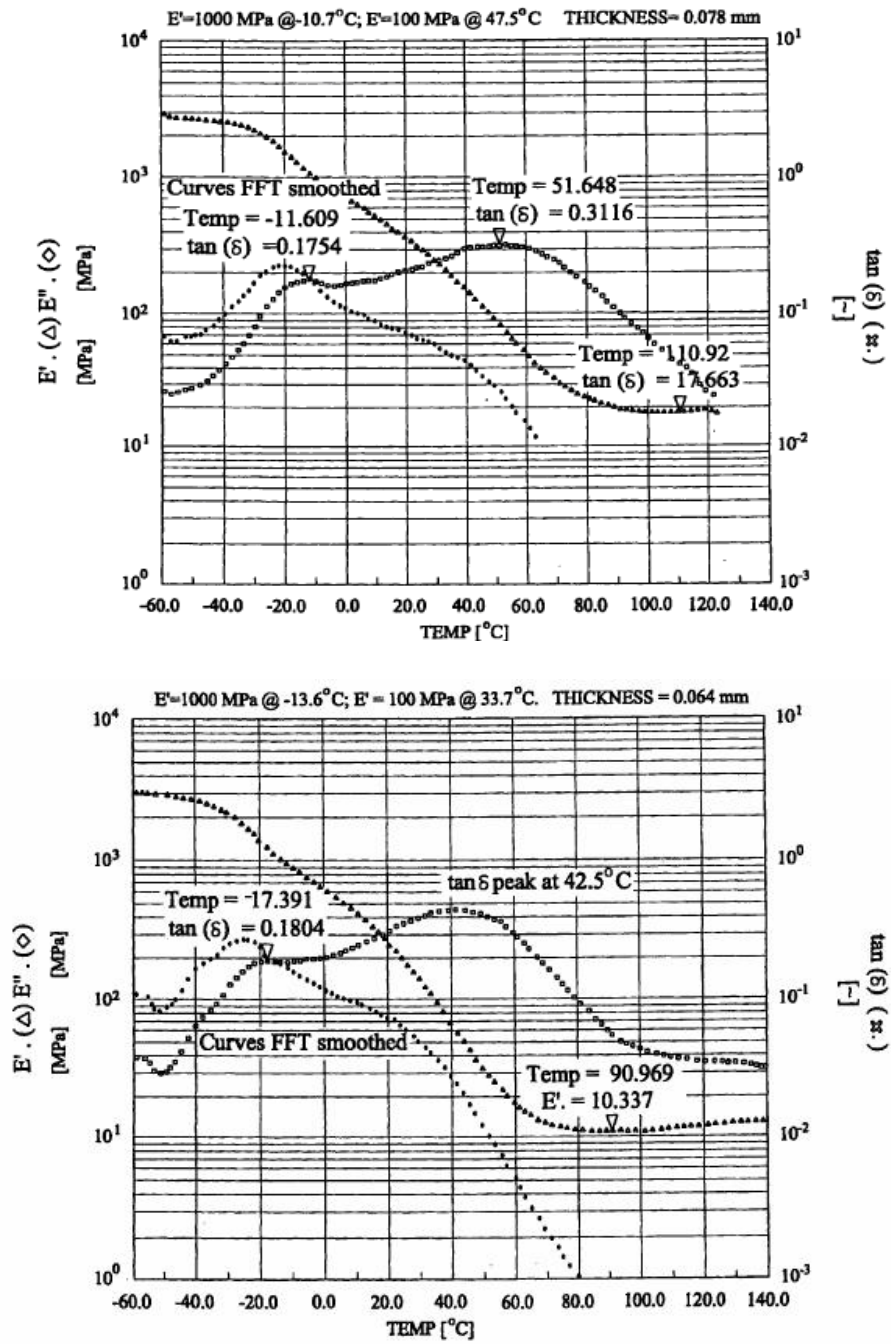


Figure 1. DMA results of formula b (top), 3% photoinitiator and formula c (bottom) 6% photoinitiator.

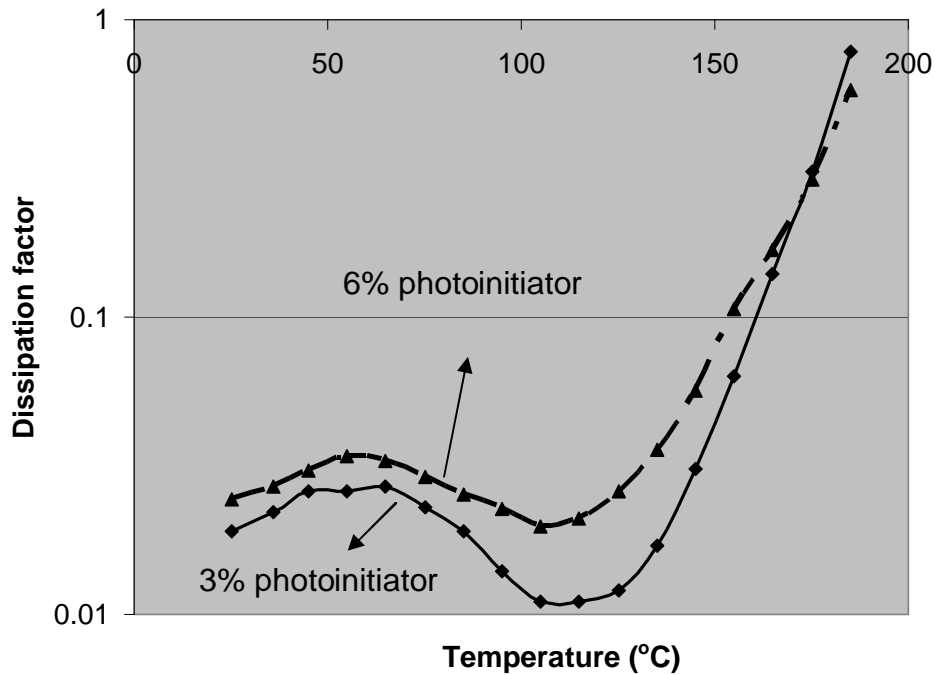


Figure 2. Effect of photoinitiator concentration on the dissipation factor.

Photoinitiator concentration also affects the dissipation factors of the cured coatings, as shown in Figure 2. Dissipation factor is expressed as the ratio of the resistive power loss to the capacitive power. Higher dissipation factor means that the dielectrics are not good insulator. The energy loss in low frequency (60 Hz) is mainly due to the electrical conduction of the dielectrics. In dielectrics, charge carriers, such as electrons and ions, move under electrical field by hopping through defects. Phase boundaries and free photoinitiator are defects in these coatings, and they both increase the dissipation factor. That is the reason that higher photoinitiator level increases the dissipation factor.

Dissipation factor generally increases with the temperature for most dielectrics, because temperature increases the mobility of charge carriers. However, these UV curable dielectrics exhibit dissipation factors that are unusually dependent upon temperature. Dissipation factor has a peak around 50 °C, and it reaches the lower point at 110 °C. Coincidentally, dissipation factor peaks around the glass transition temperature of the cured coating. When the temperature reached the T_g of the coatings, the polymers become more like a liquid, which is more homogenous with less defects, such as phase boundaries. That is the reason that dissipation factor start to drop when temperature of the dielectrics reaches T_g. On the other hand, temperature increases also increase the mobility of charge carriers. Therefore, dissipation factor increase very quickly after temperatures reach 110°C and above. It was found that small amount of pigment has little effect on the dissipation factor of the coatings, as shown in Figure 3.

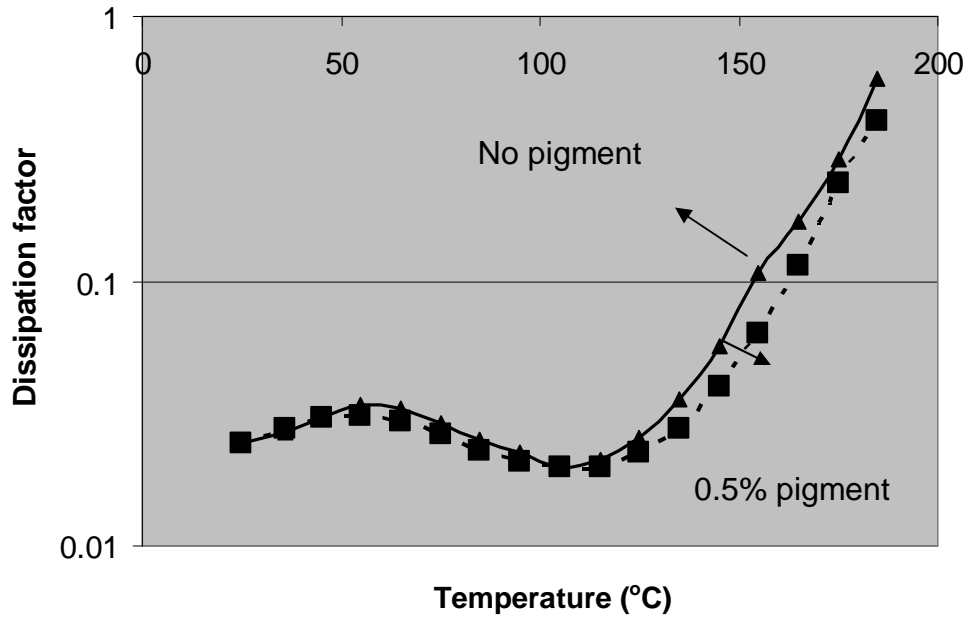


Figure 3. Effect of Pigment on the dissipation factor of coatings.

Breakdown strength of the dielectric coatings is another important factor that defines the highest electrical field that the dielectrics can withstand without breakdown. Figure 4 shows the breakdown strength of coating made from formula-C.

Compared with ordinary plastics, such as PET, polystyrene and polypropylene, the UV curable dielectrics have high dissipation factor and low breakdown strength. These properties could mainly be due to the fast photopolymerization that creates defects in the coatings and the remaining low-molecular weight photoinitiators.

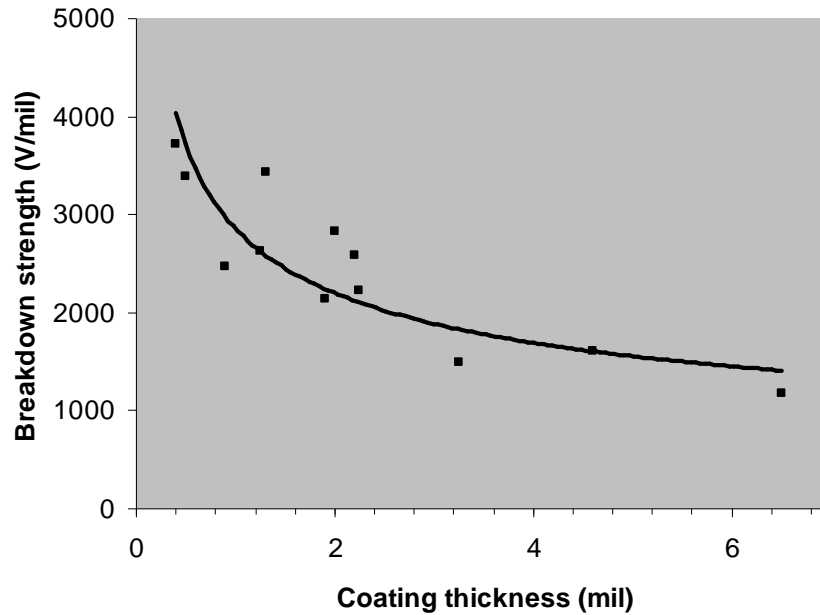


Figure 4. Breakdown strength of coatings from formula-c.

Conclusion:

UV-curable dielectrics were developed for transformer coils. The dielectrics meet all the requirements needed by the transformer coils. The cured coatings are flexible and have high elongation and strong adhesion on the metal substrates to allow the bending of the electrical conductors. As insulating layers on electrical conductors, the coatings have good insulating properties both at low and high temperatures.

¹ Vadim V. Krongauz, Stephen C. Lapin, and Anthony J. Tortorello; US patent 7,109,253 B1, 2006.