



Insight — Application Note 2.03

Linear vs. Logarithmic Scales— Seeing All the Information

Introduction

During cure the conductance G_{MUT} of a thermoset between the electrodes of a sensor changes by several orders of magnitude. Before processing starts, conductance is normally low because the material is either in a solid state or is at a temperature too low for significant crosslinking. Typically the thermoset is cured by heating to an elevated temperature. As the material becomes warm and softens, the conductance increases. The rate of crosslinking increases with temperature, also, and at some point its influence dominates and the material begins to harden—conductance reaches a maximum at this time then decreases as the material becomes more viscous then rigid. By the end of cure the conductance may have decreased by a factor of 100 or more from its peak value.

Plotting conductance on a logarithmic scale is the optimum method for seeing all the information available from dielectric measurements.

Data plotted against linear scales

Figure 3-1 shows how conductance varied during cures of several samples from the same batch of sheet molding compound (SMC).

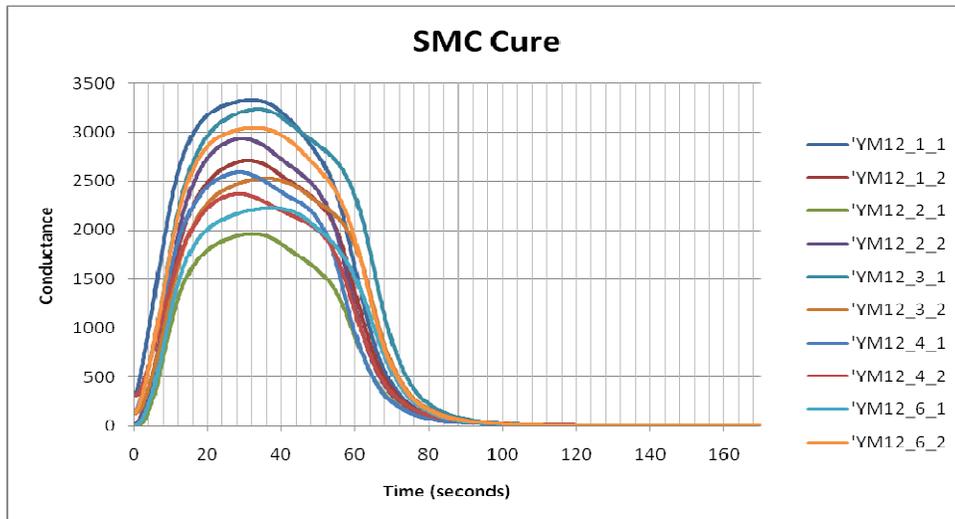


Figure 3-1
SMC conductance during cure on a linear scale

The data are plotted against a linear scale and reveal considerable sample to sample variation, with a 140% difference between the maximum and minimum values of peak conductance.

At first glance the lack of consistency casts doubt about the usefulness of dielectric cure monitoring; however, to avoid misinterpretation, it is necessary to understand the factors that determine conductance. Figure 3-2 shows a model of the conductance and capacitance of a material under test (MUT) between parallel plate electrodes. Note that only conductance is relevant in this section.

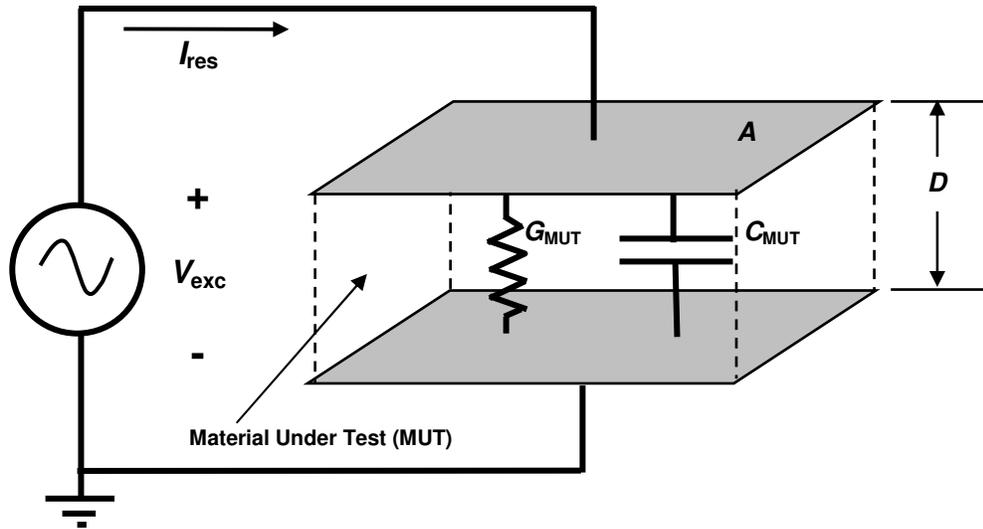


Figure 3-2
Electrical model of dielectric Material Under Test

Conductance and conductivity

Conductance is a bulk property that depends both on the geometry of the electrodes as well as on the **conductivity** of the material between them. Like density, conductivity is a property that is independent of the quantity of material. During cure this conductivity changes with time, and the measured conductance as a function of time, $G_{MUT}(t)$, is given by equation 3-1.

$$(eq. 3-1) \quad G_{MUT}(t) = \sigma(t) (A/D) \quad (\text{ohm}^{-1})$$

Where: $\sigma(t)$ = time varying conductivity ($\text{ohm}^{-1}\text{-cm}^{-1}$)
 A/D = ratio of electrode area to electrode separation (cm)

Several factors determine the time varying conductivity, which is given by equation 3-2.

$$(eq. 3-2) \quad \sigma(t) = n q \mu(t) \quad (\text{ohm}^{-1}\text{-cm}^{-1})$$

Where: n = free ion concentration (cm^{-3})
 q = charge of free ions (coulombs)
 $\mu(t)$ = free ion mobility ($\text{cm}^2 / (\text{V}\cdot\text{s})$)

Assuming the free ion concentration and the charge of the free ions do not change during cure, then only the change in free ion mobility, $\mu(t)$, affects conductivity and ultimately conductance. In a thermoset, perhaps the most significant factor determining mobility is the crosslinking among monomers. As crosslink density increases, the growing molecular network impedes the flow of ions and reduces mobility.

Combining equations 3-1 and 3-2 produces the following expression:

$$(3-3) \quad G_{\text{MUT}}(t) = [n (A/D) q] \mu(t)$$

In reality, the value of $[n (A/D) q]$ may change from sample to sample and test to test. The free ion concentration, n , increases with conductive additives and decreases with non-conductive filler. The geometry (A/D) of the electrodes may differ from sensor to sensor because of variations in fabrication or set up. The free ion charge normally does not change but is included with the terms in brackets for simplicity. Equation 3-3 may then be reduced to:

$$(3-4) \quad G_{\text{MUT}}(t) = [B] \mu(t)$$

Here $B = n (A/D) q$, the variable terms unrelated to curing. Expressed logarithmically, equation 3-4 becomes:

$$(3-5) \quad \log_{10}(G_{\text{MUT}}(t)) = \log_{10}(B) + \log_{10}(\mu(t))$$

From equation 3-5, plotting the measured conductance on a logarithmic scale captures the entire range of $G_{MUT}(t)$ caused by the mobility, which can change by several orders of magnitude during cure.

Plotting on a logarithmic scale also produces an offset, which is $\log_{10}(B)$, caused by the terms unrelated to curing. If the free ion concentration and the electrode geometry are constant for a particular sample and test, then *the result is a constant offset from the baseline behavior of $\log_{10}(\mu(t))$.*

Effect of mixing and fillers

For a single batch of liquid resin, good mixing can produce a homogeneous free ion concentration, and the measured conductance can be uniform from sample to sample. In contrast, a material like SMC has a high content of non-conductive chopped glass fibers mixed with polyester, vinyl ester or epoxy resin. This composite is semi-solid, is difficult to mix well, and as a result different samples may have different ratios of fiber to resin. The measured conductance of SMC is therefore likely to vary among samples from a single batch, as illustrated in Figure 3-3.

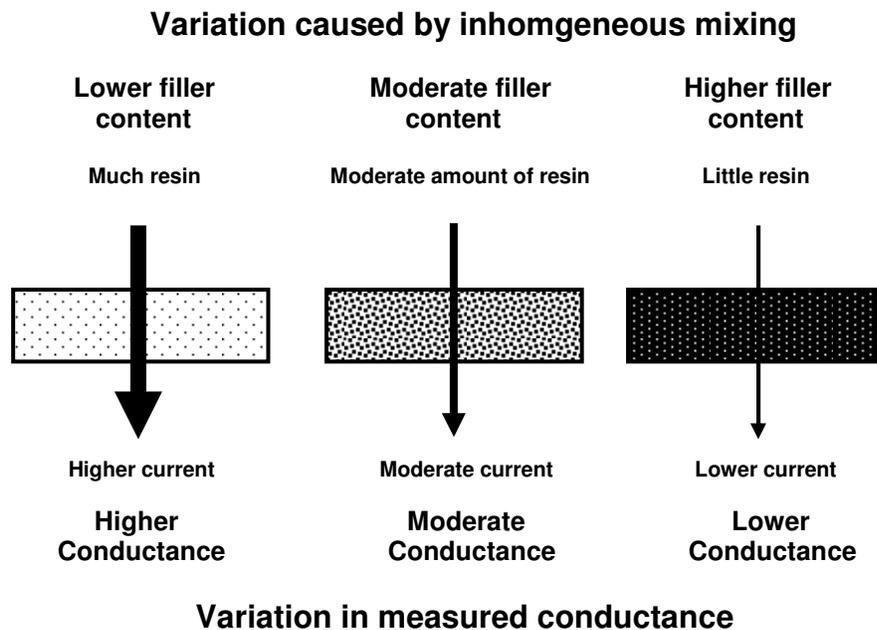


Figure 3-3
Addition of non-conductive filler reduces amount of conductive resin

Data plotted against logarithmic scales

When the data of Figure 3-1 are plotted on the logarithmic scale, the curves are largely parallel to one another and differ by an offset in conductance. This offset is typically caused by sample-to-sample variation in filler content, which does not affect the cure rate.

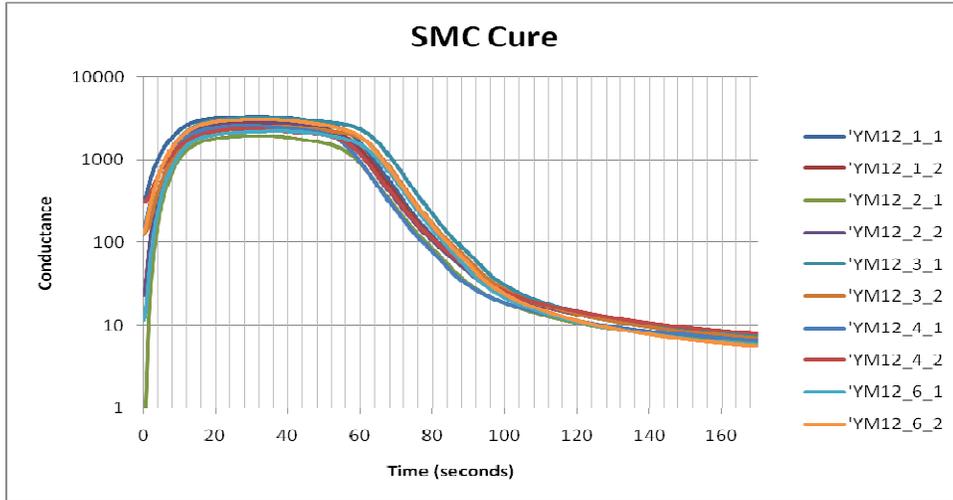


Figure 3-4
SMC conductance during cure on a logarithmic scale

Plotting conductance against logarithmic scales has significant advantages compared to linear scales:

- The entire range of conductance is visible
- Only factors that affect cure determine the shape of the conductance curve
- Factors that do not affect cure, such as variations in filler content or sensor geometry, determine offsets of the conductivity curve but not its shape



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