Insight — Application Note 2.05

Loss Factor and Ion Viscosity

Introduction

Dielectric permittivity ε is a quantity with real and imaginary parts:

(Eq. 5-1) $$\varepsilon^* = \varepsilon_0 (\varepsilon' + i\, \varepsilon'') = \varepsilon_0 [\varepsilon' + i\, \sigma / (\varepsilon_0\, \omega)]$$

Conductivity σ is the sum of frequency independent (σ_{DC}) and frequency dependent (σ_{AC}) components[1], as expressed below:

(Eq. 5-2) $$\sigma = \sigma_{DC} + \sigma_{AC}$$

In an oscillating electric field, σ_{DC} arises from the flow of mobile ions while σ_{AC} arises from the rotation of stationary dipoles. Loss factor ε'' is a measure of the dissipation, or loss, of electromagnetic energy as heat and is given by:

(Eq. 5-3) $$\varepsilon'' = \sigma / (\omega\, \varepsilon_0) = (\sigma_{DC} + \sigma_{AC}) / (\omega\, \varepsilon_0)$$

During thermoset cure, σ_{DC} tends to dominate in the early part of cure, when the material is most conductive. Frequency independent conductivity also may dominate throughout cure at low frequencies. During these times the loss factor may be approximated as:

(Eq. 5-4) $$\varepsilon'' \approx \sigma_{DC} / (\omega\, \varepsilon_0)$$

In this case, loss factor is inversely proportional to frequency. For example, if the excitation frequency decreases by a factor of 10, loss factor increases by the same factor of 10—this relationship identifies when σ_{DC} dominates the dielectric response and can indicate cure state.

During the latter part of cure, frequency *dependent* conductivity due to dipoles may dominate the dielectric response, especially at higher frequencies. It is important to identify these times and frequencies to avoid misinterpreting data for purposes of cure monitoring.

1. The real part of relative permittivity, or relative dielectric constant, ε' also has frequency independent and frequency dependent components, but they will not be treated in this application note.

 © 2017 Lambient Technologies

Cure monitoring with multiple frequencies

Figure 5-1 shows dielectric data at multiple frequencies during the cure of an epoxy resin. A plot of loss factor can reveal when frequency independent conductivity σ_{DC} dominates the dielectric response. In the early part of this cure, loss factors for 10 Hz, 100 Hz, 1 kHz, and 10 kHz all are inversely proportional to frequency.

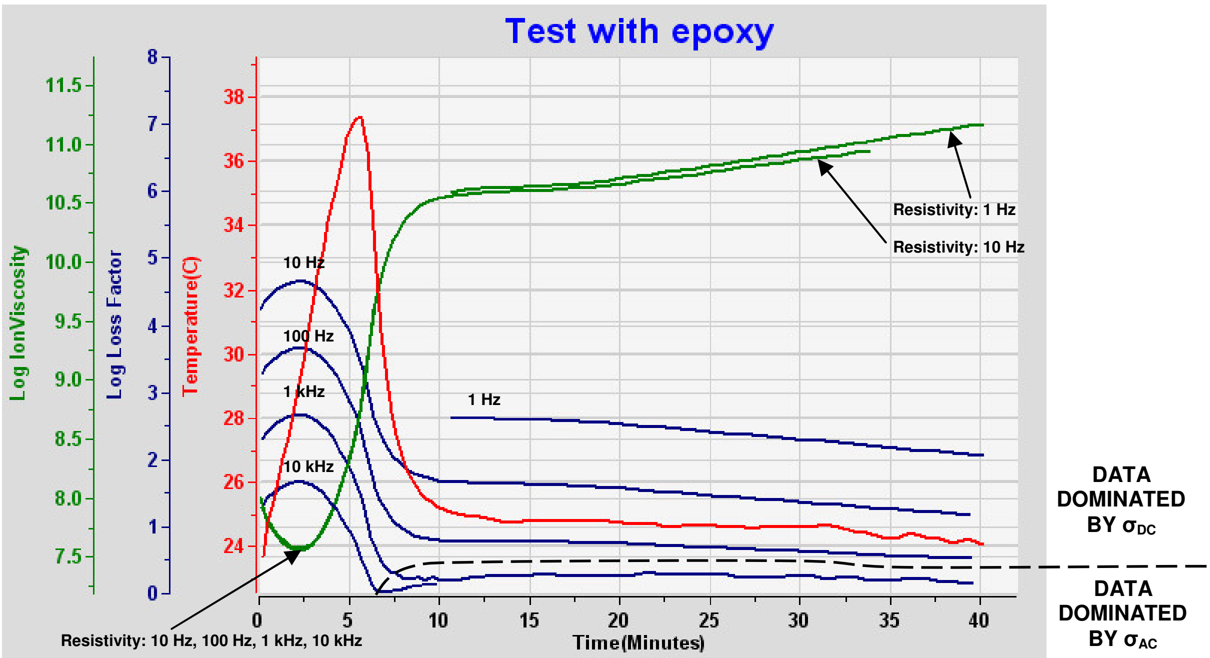

Figure 5-1
Multiple frequency data from epoxy cure

In the latter part, however, only loss factors for 1 Hz, 10 Hz and 100 Hz are inversely proportional to frequency.

Resistivity ρ is the inverse of conductivity, as expressed in equation 5-5:

(Eq. 5-5) $$\rho = 1 / (\sigma_{DC} + \sigma_{AC}) = 1/(\omega\,\varepsilon_0\,\varepsilon'')$$

When frequency independent conductivity σ_{DC} dominates the data, then resistivity is also largely frequency independent. Frequency independent resistivity ρ_{DC} is called *ion viscosity*, and is characterized by the overlap of resistivity at multiple frequencies, as shown in Figure 5-1.

During thermoset cure, ion viscosity typically increases proportionately with mechanical viscosity until they diverge around the time of gelation. Even

 © 2017 Lambient Technologies

after mechanical viscosity becomes infinite, however, the crosslinking reaction continues and the growing polymer network still presents greater and greater resistance to the flow of ions. Consequently, frequency independent resistivity ρ_{DC}—ion viscosity—can be used for determining cure state throughout the entire cure.

Lambient Technologies LLC
649 Massachusetts Avenue, Cambridge, MA 02139
857-242-3963
www.lambient.com
info@lambient.com

 © 2017 Lambient Technologies