Insight — Application Note 3.08

Ion Viscosity and Loss Factor

Permittivity and loss factor

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

(Eq. 8-1) $$\varepsilon^* = \varepsilon_0\,(\varepsilon' + i\,\varepsilon'') = \varepsilon_0\,[\varepsilon' + i\,\sigma / (\varepsilon_0\,\omega)]$$

Where: $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm (permittivity of free space)
$\omega = 2\pi \cdot f$ (angular frequency)
f = oscillation frequency (Hz)

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

(Eq. 8-2) $$\sigma = \sigma_{DC} + \sigma_{AC}$$

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 chapter.

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

(Eq. 8-3) $$\varepsilon'' = \sigma / (\omega\,\varepsilon_0) = (\sigma_{DC} + \sigma_{AC}) / (\omega\,\varepsilon_0)$$

During the early part of cure, when a thermoset is most conductive, σ_{DC} tends to dominate the dielectric response across a broad range of frequencies. At sufficiently low frequencies σ_{DC} may also be the significant component through the entire cure. When σ_{DC} dominates cure behavior, σ_{AC} is insignificant and loss factor may be approximated as:

(Eq. 8-4) $$\varepsilon'' \approx \sigma_{DC} / (\omega\,\varepsilon_0)$$

In this case, loss factor is inversely proportional to frequency. For example, if the excitation frequency (ω) *decreases* by a factor of 10, loss factor *increases* by the

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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 when studying cure.

Cure monitoring with multiple frequencies

Figure 8-1 shows dielectric data at multiple frequencies during the cure of "five-minute epoxy." 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.

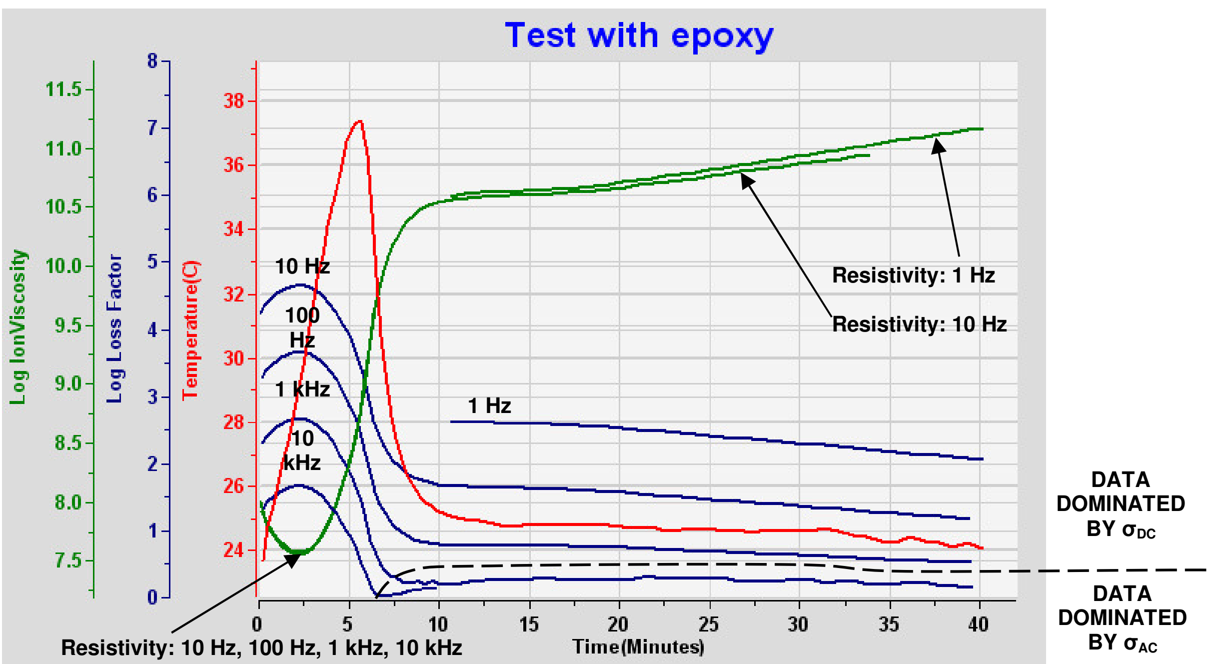

Figure 8-1
Multiple frequency data from cure of five-minute epoxy

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 8-5:

(Eq. 8-5) $$\rho = 1 / (\sigma_{DC} + \sigma_{AC}) = 1/(\omega\, \varepsilon_0\, \varepsilon'')$$

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When frequency independent conductivity σ_{DC} dominates the data, resistivity is also largely frequency independent. Frequency independent resistivity ρ_{DC} is called *ion viscosity*, and is characterized by the overlap of curves at multiple frequencies, as shown in Figure 8-1.

During thermoset cure, the change in ion viscosity is typically proportional to the change in mechanical viscosity until they diverge around the time of gelation (See Figure 7-4). Even after mechanical viscosity becomes immeasurable, however, crosslinking 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 through the entire cure.

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