

RHEOLOGY; Materials in Motion

The Science of circuit board lamination.

by

" παντα ρει"

or 'Everything Flows', was first documented by Heraclitus, a 5th Century B.C. Metaphysician. It was not until some 2200 years later that rheology was established as the science of material deformation and flow when Sir Isaac Newton defined viscosity as the ratio of shear stress to shear rate.

Understanding rheology on a practical and theoretical basis replaces some of the magic in the lamination process with science. Applying this science to the multilayer lamination process can mean the difference between a robust process in the middle of a process window and one that can occasionally drift out of control.

VISCOSITY

Materials respond to stress in many ways. Lubricate, spread and squeeze are non-technical words to describe rheological response. Materials can be strained, ruptured, made to flow or move or accelerate when subjected to stress. The basic relationship of stress and strain defined by Newton is:

$$F/A = \mu * V/L$$

where F/A = shear stress (force per unit area),
 μ = a proportionality constant (viscosity)
V/L = the velocity per layer thickness (shear rate).

From this relationship, the ratio of shear stress to shear rate defines viscosity¹.

Many factors exert an effect upon viscosity. Fluids with higher molecular weights usually have higher viscosities. More molecular branching and molecular entanglement also results in higher viscosity. Increases in temperature reduces viscosity by increasing molecular activity and reducing entanglement. Dilution of higher molecular weight materials with lower molecular weight species will also lower viscosity by reducing molecular entanglement.

RHEOLOGICAL TESTING

Selecting from the various ways to measure viscosity depends upon the material studied and the range of viscosity under consideration. For prepregs, the parallel plate rheometer is favored, due to its flexibility in testing conditions. This is because the instrument can be used to model lamination press cycles without putting expensive product at risk.

Contained within a precision oven, fitted with an oscillating bottom plate and a torque transducer on the top plate, the parallel plate rheometer can be programmed with a heating profile, oscillating frequency and strain to produce a stress within a sample. Samples of prepreg dust are sifted to remove glass fiber reinforcement (since fabric fragments can result in unrepeatable readings).

The instrument computer compares the material stress to the inputted strain, and separates the information into the tan delta (phase angle), the storage (in phase) and loss modulus (out of phase) components. The instrument computer mathematically derives viscosity from this information. The instrument provides a profile that shows where the prepreg melts, softens, flows and gels, thus defining a process window for the lamination process (which has been simulated in the instrument).

PREPREG CHARACTERIZATION

Resin flow testing does not always correlate with production results. For example, the Resin Flow Test (IPC-TM-650; method 2.3.17B) calls for a 200 psi lamination pressure on a 4 inch by 4 inch layup of 4 plies. When considering the Resin Flow Parameter²:

$$F = C * \frac{P}{A} \int \left(\frac{1}{\mu} \right) dt$$

where F = Resin Flow Parameter
C = Geometry Constant
P = Pressure
A = Area
 μ = viscosity
t = time

we see that resin flow is proportional to the Pressure to Area Ratio, as well as the viscosity profile provided by the press cycle. In the IPC Resin flow test, the Pressure to Area ratio is 12.5. This pressure to area ratio can be 10 to 15 times higher than the pressure to area ratios of production laminations of multilayer boards. From this, it is easy to see why the resin flow test does not correlate well with prepreg rheology. The Scaled Flow Test (IPC-TM-650; method 2.4.38A) provides more accurate information about the rheological differences in prepregs, based upon thickness yield per ply. Because of the lower pressure to area ratio in testing, the Scaled Flow Test correlates better to rheological differences in prepregs than the Resin Flow Test.

LAMINATION

The lamination press may be considered a rheometer of sorts. While it does not provide units of viscosity, observations of the type and amounts of flash around the edges of laminate books provide the lamination engineer with rheological information about the press cycle. The amount of flash reveals if resin flow was excessive, inadequate or sufficient. As a qualitative instrument, edge flash can be used to determine whether the press cycle is providing consistent resin flow.

Over the years, the lamination process has been empirically determined to provide a good, robust process window. Some of the observations about prepregs include:

Changes in heating rate can induce changes in melt viscosity profile (Figure 1).

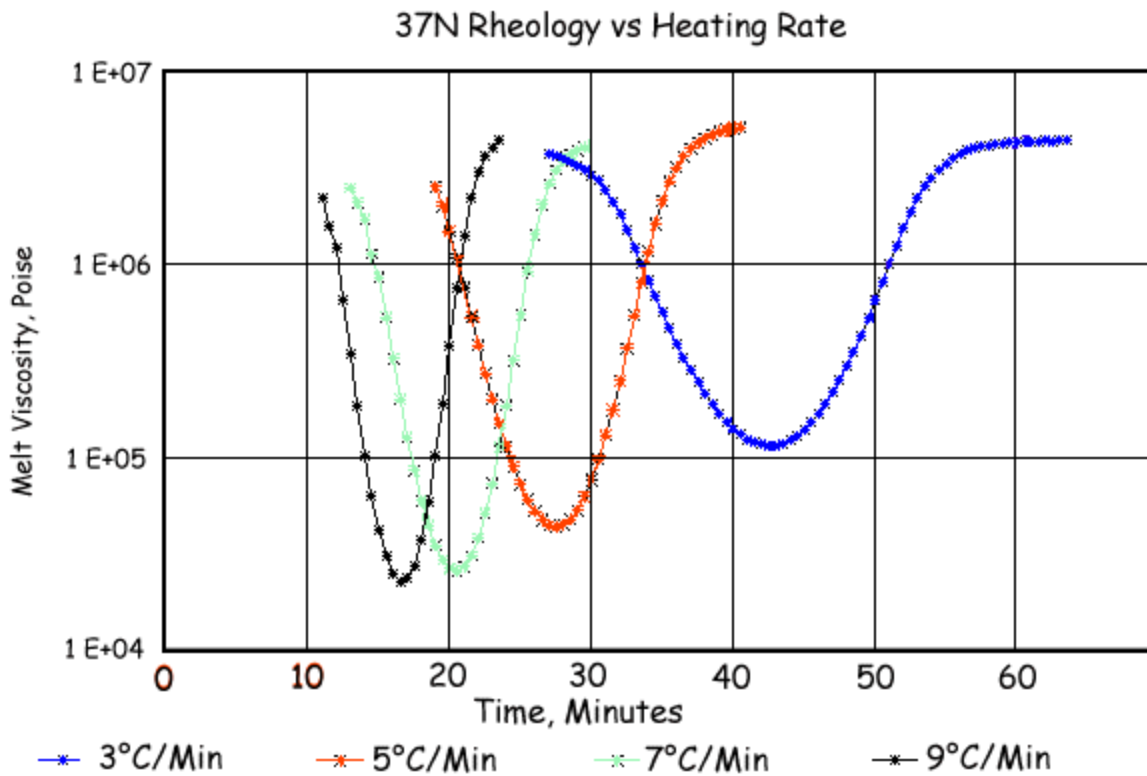


Figure 1.

When preregs are heated more quickly, they become more fluid or "juicier", to provide more flow during lamination. This is utilized to provide more flow in lamination. When taken to extreme, there can be so much flow, or uneven flow in a multilayer package so as to induce the appearance of dryness (resin starved glass), voids (gel occurs too rapidly) or thickness tolerance problems (too much edge flow).

When preregs are heated more slowly, they become less fluid. This is done to reduce the amount of flow and flash during lamination. If the heating rate is too slow, there may be voiding or incomplete encapsulation of traces, or poor adhesion to inner layer circuitry.

These observations are readily explainable. In considering the two opposing activities- resin melt vs resin gelation, a slower heating rate provides the resin time to react and advance its molecular weight at elevated temperatures before reaching minimum viscosity. The process can be considered to be a "thermal aging" effect, whereby the prepreg shows a higher melt viscosity. With faster heating rates, there is considerably less cross linking of the resin, so there is less time for thermal aging before the prepreg reaches its minimum viscosity, so the prepreg shows a lower melt viscosity.

In considering the effects of Table 1, two developments have been used to minimize the disadvantages in press cycle extremes.

The first method has been to delay the application of full pressure until the prepreg has reached a molten state. By using a contact pressure of 50 to 100 psi until the prepreg becomes a melt (about 80°C-105°C for epoxies and 100-135°C for polyimides). At this fluid stage, where the resin has just become molten,

but before the resin reaches its minimum viscosity (and maximum cross-linking rate) the full lamination pressure is applied. By waiting until the resin has become molten, the greater fluidity in the resin creates less shear stress in the elastic melt region and there is less glass reinforcement deformation. When parts are cooled, there is less "snap-back", and registration is improved. This approach also improves oxide bond strength by reducing shear on oxidized inner layers.

Experimental work has shown that plateau cycles can be used when a particularly difficult fill configuration requires a lot of resin fill (for example, heavy opposing copper planes) and when excessive resin flow results in poor dielectric thickness control and crushed or deformed inner layers.

With a plateau cycle, the material is quickly heated to a temperature just before the point of minimum viscosity. The fast temperature rise provides the advantage of a lower minimum melt viscosity than is furnished with a slower heating rate, where the resin is thermally aged before full melt. Since the package is maintained, and not ramped with additional heat, there is a slower reaction rate and longer gel time. After a plateau of 15 to 20 minutes, the material is brought to final cure temperature.

The plateau cycle has the advantages of both the fast heating rate (for low viscosity filling and wetting) and the slow heating rate (for longer working time, less taper, etc.). As a result, wetout and encapsulation is improved, and more uniform printed circuit board resin retention provides for better dielectric thickness control.

SUMMARY

Prepreg rheology provides the lamination engineer with several perspective views of the lamination process. The parallel plate rheometer offers the advantage of observing the effects of process changes. Modelling can be done on a laboratory instrument without putting expensive product at risk.

More educated process changes can be made with rheological information. An understanding of the critical parameters of a given resin system allows for a more robust lamination process. As circuit configurations change, an understanding of rheology can be used to counterbalance rheological effects. Delayed pressure application temperatures (kiss cycles) and plateau cycles can be used to new push prepreg to new performance levels in the lamination process.

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