| APPLICATION NOTES

RHEOLOGY; Materials in Motion
The Science of Circuit Board Lamination

I. Introduction

Circuit boards have become more intricate and material performance and reliability in the multilayer board manufacturing process is more critical than ever before. Prepregs must readily meet the new demands of today's electronic product designs. The application of prepreg rheology in the lamination cycle can help characterize and design prepregs to allow enhanced performance under the increased demands of miniaturization, SMT and advanced packaging designs.

Considering the advances in computing and electronics over the past ten years, it is hard to imagine the developments we will see in the next ten. Even as electronic products take on smaller sizes for speed, convenience and portability, these devices need to provide additional functionality and performance. Because of this, multilayer boards contain much finer lines and spaces as well as increased layer counts. Prepregs must fill more difficult circuit geometries than ever before. The tight requirements for dielectric thickness control must be maintained for controlled impedance

applications. Prepregs must wet, fill and encapsulate very well, yet not flow so much as to create a multilayer board with the profile of an official NFL football.

In these days of tough international competition and shortened development cycles, productivity must constantly increase so that companies can remain competitive and profitable in the marketplace. The lamination press cannot be a bottleneck. Deliveries must be just-in-time and products must work right the first time. Stack heights are being increased and cycle times decreased to improve manufacturing throughput. In addition, new prepreg and laminate materials with higher performance properties are available to help increase yields through the MLB manufacturing process. Improved resins, blends, new resins and new additives come with claims of improved performance, but they "are not your father's Buick" and will require rigorous process development both at the supplier and processor levels. If manufacturing procedures are not carefully developed through Statistical Product Development and SPC, the processing window will appear to be very small or elusive.

The Science of Rheology, when applied to the multilayer lamination process, can reduce reliance on some of the "magic" in the lamination process with data about material deformation and fluid mechanics. An understanding of prepreg rheology can turn the lamination process away from the remnants of EVOP, SWAG or other rituals (like crossing one's fingers or mumbling a quick prayer as the press closes). This can mean the difference between a process that is robust, in the middle of its process window, or one that occasionally drifts out of control when lamination parameters do not line up exactly.

II. Theoretical Basis

" Panta Rei" or the observation '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 "art" in the lamination process with science. Applying this 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 some of the 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 viscosity. 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. Increase 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.

The definition of these relationships, along with Newton and Baron von Leibniz' independent development of Calculus, accelerated developments in the science of rheology and measurement of fluid viscosity. There are many different ways to measure viscosity, depending on the type

of material being studied and the viscosity range of the fluid under consideration. This article will not attempt to describe them all. A good source for information on rheology basics as well as instrument types for polymer melts would be Cogswell's "Polymer Melt Rheology" (See bibliography)

The coefficient of viscosity (or simply viscosity), is the measure of resistance to an applied force, or the resistance to flow. This is modeled by two plates separated by a fluid. One plate is stationary, while the other is moving at a constant speed, maintaining a constant distance from the stationary plane. When such a force is applied, the layer of fluid immediately adjacent to the moving plane moves nearly at the speed of the moving plane, while subsequent layers, closer to the stationary plane move more slowly. This establishes a velocity gradient between the plates.

When a fluid more effectively transfers its momentum to adjacent layers, there would be less of a velocity gradient, and the observation in our plate model is that the fluid layer has a high viscosity. When a fluid does not effectively transfer its momentum to adjacent fluid layers in our plate model, the velocity gradient is more pronounced and the fluid has a low viscosity. This sets up the basis for a rheometer. When the shearing plates are of a known geometry and at a fixed distance, a calibrated strain can be applied to the plate. A transducer, attached to the stationary plate, can measure the induced stress in the test sample. By determining the ratio of the shear force (force per unit area) to the shear rate (velocity gradient), the flow resistance, or viscosity is derived.

Factors Affecting Viscosity

In the realm of polymer processing, it is important to consider the factors that affect viscosity. These are:

A. Temperature Effects

The presence or absence of heat determines how active molecules are in a fluid. As solids and liquids increase in temperature, molecules become more active, and less likely to remain entangled, so it is not surprising that the viscosity tends to decrease as temperature increases. In our shear plate model, the molecules are less likely to remain entangled when heated, so the velocity gradient will be more pronounced, resulting in a lower viscosity.

B. Concentration Effects

High viscosity polymers can be lowered in viscosity by dilution with low molecular weight polymers. The low molecular weight polymers can act as a "slippage plane" in our simple shear plate example where the fluid has a more pronounced velocity gradient between the plates. Low viscosity components can act as lubricants or plasticizers for the larger molecules, to keep the larger molecules from entangling. (Moisture in prepreg can lower the apparent melt viscosity because it acts like a plasticizer.)

C. Molecular Weight & Distribution Effects

Molecular size can affect the intrinsic viscosity of materials. Smaller molecules tend to have lower viscosities. As the size of a molecule increases and the molecular weight increases, the tendency will be towards higher viscosities.

D. Molecular Branching & Chain Diameter Effects

As molecules increase in branching and chain diameter, the more likely they are to entangle to distribute shear stress in our shear plate model. This results in a higher observed viscosity.

E. Shear Effects

Newtonian Fluids

Fluids are considered Newtonian when the coefficient of viscosity remains constant over changes in shear stress. This means the viscosity remains constant, regardless of the applied shear stress.

Non-Newtonian Fluids

Fluids that exhibit a change in viscosity with a change in the shear rate are known as Non-Newtonian fluids (Figure 2.) To be meaningful, viscosity values should be reported with the shear rate used when measurements are reported.

Other Responses to Shear Stress

It is useful to be aware of the various types of response to shear stress. The following types of response can occur when a plastic or fluid is subjected to shear stress:

1. A Bingham plastic, or "true plastic," flows only after a certain yield point has been exceeded as the shear stress is increased. (Chewing gum is an example of a Bingham plastic).

2. Pseudoplastic materials appear to have a yield stress where flow increases dramatically with increases in shear stress. (Paper pulp is an example of a pseudoplastic material).

3. Dilatant materials show high flow under very low shear stresses, but further increases in shear rate result in lower flow. These are also referred to as shear thickening or inverted plastics. (Quicksand is an example of a dilatant substance)

4. Thixotropic materials are the opposite of dilatant materials. These materials will increase in flow rate with increases in agitation or increases in shear stress. When agitation or shear stress is stopped, hysteresis occurs. Generally, the material will thicken, but less shear stress is required to create a given flow compared to the first application of shear stress. (Paint for example, flows when brushed, yet does not sag afterwards).

5. Rheopectic substances are materials that when periodically sheared will "set" or build in viscosity rapidly. The apparent viscosity of a rheopectic substance will increase with time under a constant shear stress. (A thick mixture of cornstarch in water is rheopectic.)

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. It is an instrument that has been widely used in one form or another since the 1950's.

The instrument can be envisioned as a set of parallel plates contained within a programmable oven. The oven is used to provide either an isothermal (steady state) or programmed heat ramp. This makes the instrument ideal for characterizing a dynamic manufacturing process such as a multilayer board lamination cycle rather than a quick isothermal test such as a flow or gel test.

Fitted with an oscillating bottom plate and a torque transducer on the top plate (see photo above), 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 input strain, and separates the information into the tan delta (phase angle), the storage (in phase) and loss modulus (out of phase) components. The instrument's 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 baseline for the lamination process (which has been simulated in the instrument).

The operator programs the heating profile, test frequency and strain into the instrument. The sample (prepreg dust that has been removed from the

reinforcement and sifted to remove reinforcement fibers) is tested without reinforcement because within the parallel plates, fabric reinforcements result in strange, often unrepeatable results. (Note: In prepregs from which neat resin cannot be removed it is possible to use the prepreg itself, but the glass influence makes results more difficult to interpret and comparisons to pure resin testing are moot.)

III. Application to Lamination

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. Consider the Resin Flow Parameter:

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

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 which will be driven 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 guide, 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).

When prepregs 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, or "flash").

When prepregs 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
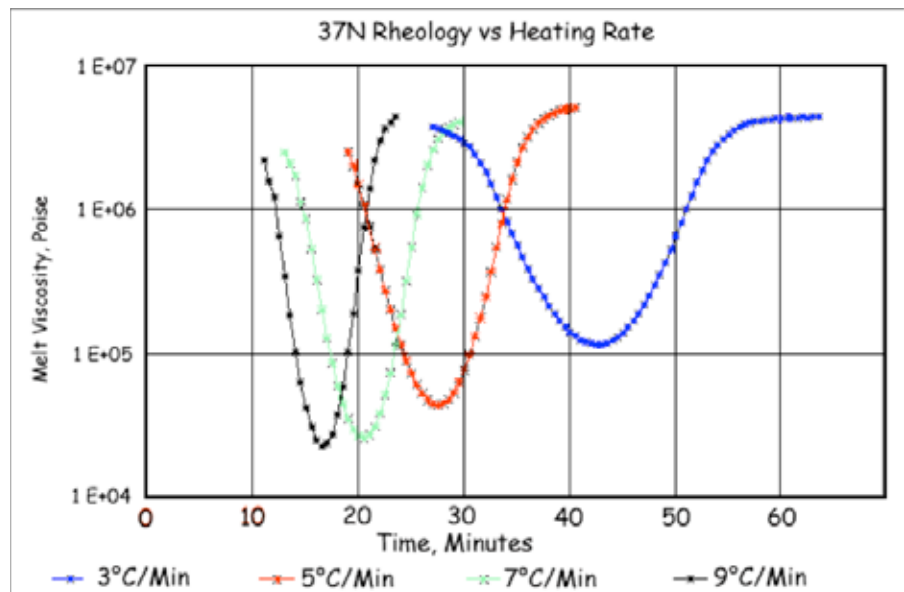

Figure 1

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 Figure 1, several approaches can be used to optimize flow and fill.

Adjusting the rate of heat up can make significant differences in flow. Faster heat up rates will result in lower melt viscosity and more flow, while slower heat up rates will result in higher viscosity and less flow. Balancing heat up rate with pressure gives the process engineer a good opportunity to get the flow he needs to fill and bond, without resulting in too much flow or on the other hand, poor fill and inadequate wetting.

In the past a lot of laminators have used a "kiss cycle" in which they delay applying 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.

Note: The use of a kiss cycle is not recommended by this author unless there is a flow issue to be resolved, since use of a kiss cycle depends on good control of the temperature inside the laminate book, and because the temperature of material closest to the platens of a press will get hotter faster than that in the center resulting in a differential flow between laminates in the same book.

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, wet out and encapsulation is improved, and more uniform printed circuit board resin retention provides for better dielectric thickness control.

The fluidity curve can also be integrated to derive a Fluidity time integral or Integrated Flow. This integral has been used to compare prepregs and different press cycles. Experimental work has shown that plateau cycles can be used when a particularly difficult configuration requires a lot of fill (heavy opposing copper planes), where excess resin flow results in poor dielectric thickness control and crushed or deformed inner layers. The concept behind a plateau temperature is to quickly heat the package to a chosen temperature, slightly shy of the resin system minimum melt viscosity.

This provides the advantage of a lower minimum viscosity than is provided by a slower heating rate. By choosing a plateau temperature that is slightly lower than the minimum melt viscosity, the lower rate of reaction of the melt will result in a longer time to gelation. This plateau is usually 15 to 25 minutes long to extend resin flow. The press cycle then continues on to the final cure temperature.

Since the plateau cycle takes the advantages of both the fast heating rate cycle as well as the slow heating rate cycle, wetting is improved, uniform resin retention is achieved for thickness control.

V. Summary

Prepreg rheology provides the lamination engineer with a scientific perspective on the lamination process. The parallel plate rheometer offers the advantage of observing the effects of process changes. Modeling can be done on a laboratory instrument without putting expensive product at risk. Better prediction of the effect of process changes can be designed with appropriate 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 now push prepreg to new performance levels in the lamination process.

Prepreg rheology offers several perspectives to the lamination engineer. The parallel plate rheometer offers the advantage of observing the

effects of an actual process on the instrument. Modeling can be done on a lab instrument without having to put expensive product at risk. More educated process changes can be made with rheological information.

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