COMPOSITES 2004 Convention and Trade Show
American Composites Manufacturers Association
October 6-8, 2004
Tampa, Florida USA

Using In-Mold Impedance Sensors to Control Thermoset Plastic Molding

by

Steve Courington, Signature Control Systems

Abstract

Impedance sensing technology provides a new method for thermoset molders to monitor and control the cure process. Similar to dielectric cure monitoring, impedance technology uses the changing electrical properties of the thermoset as it cures to determine the appropriate time to end the cure. The technology uses low-voltage sensors mounted in the mold and computer software to analyze the resulting signal.

This paper reviews the implementation of impedance sensing technology in polyester sheet molding compound (SMC) and phenolic, and presents results from several production and lab applications. Results discussed in this paper will show that impedance sensing technology:

- Correlates to part properties related to cure state.
- Has worked in production molding operations since December 2003.
- Detects the effects of mold temperature changes on cure rate in the production mold.
- Automatically adjusts cure times to compensate for mold temperature fluctuations.
- Shows the impact of charge placement on cure rates across a mold when multiple sensors are installed.
- Identifies SMC flow anomalies and detects process adjustments that affect material flow.
- Identifies material variations and provides a mechanism to continually improve the SMC formulation.
- Correlates to cure related properties for mineral filled phenolics.

Impedance Sensing Theory

The technology uses in-mold sensors to measure the electrical impedance across the mold cavity during cure. The sensor is designed for harsh production environments, and is proven through thousands of cycles at high temperatures and pressures. A low level AC voltage is applied to the sensor, creating a capacitor field coupled to the opposite side of the mold cavity. Figure 1 is a schematic of the sensor installation in the mold. The applied voltage results in a complex current flowing through the material to the grounded mold surface. This current consists of both an in-phase component and an out-of-phase component, from which conductance (loss factor) and capacitance (permittivity) of the material can be derived. Figure 2 is a picture representative of the sensor design and physical layout. The white area on the sensor face is ceramic, which serves as a wear-resistant surface and isolates sensing elements from the material.

The strength of the capacitor is driven by the dielectric properties of the material between the sensor and the other side of the mold. The dielectric properties of SMC and other thermoset plastics vary during cure, due to the changing ability of dipolar molecules to oscillate in the applied electrical field. If the molecule is free to align, the electrical storage capacity (permittivity) is increased. Once cross-linking restricts the ability of the dipole to align, this capacity begins to decrease. Concurrent with alignment of the dipoles, there are losses (loss factor) that occur in the form of ionic conduction and viscous rotation of dipoles.

The changing dielectric properties of the material during cure form an impedance "signature" characteristic of the material. Figure 3 shows a typical SMC (polyester, styrene monomers) impedance signature with time in seconds shown on the x-axis and the relative conductance shown on the y-axis. Figure 3 shows that the signature initially rises as the press closes, the SMC comes into contact with the sensor, and the sensor couples with the opposing ground plane. The signature continues to rise as the compound begins to soften and ionic and molecular entities are more capable of moving within the sensor's electric field. The signature "peaks" as the compound reaches the point of gelation. After the peak, the impedance rapidly decays as the polyester and styrene react and cross-linking restricts the motion of ionic and molecular entities within the sensor's electric field. The signature then "tails" to a flat-line condition as the remaining styrene-styrene reaction takes place.

Technology Implementation

The impedance sensors are connected to a computer controller with signal conditioning and data acqui-

sition electronics to measure the impedance signal. The controller also communicates with the press control system via standard discrete inputs and outputs. A press output signals the controller at the beginning of the cure cycle. The controller turns on the sensor voltage and begins monitoring the impedance signal when this signal is received from the press. The controller is also wired to signal the press to open instead of the normal cure timer.

Software analyzes the impedance data during the cure using a real-time algorithm called a **rule base**. The rule base is normally set up to identify the point at which adequate cure is achieved. Referring to Figure 3, the rule base first identifies the impedance signature's peak, which correlates to the gelation zone. Once it identifies this point, the rule base then identifies a slope value near the transition to a flat. The proper slope to end the cure is determined empirically by measurement or observation of an applicable part property. Blistering before or after post-bake is often used for SMC parts to identify the point of adequate cure. Porosity before or after post-bake is often used for phenolic parts to identify the point of adequate cure. In the case of SMC, adequate cure is typically reached when the impedance data becomes flat.

Once the software identifies the point of sufficient cure, the controller signals the press to open or stop the curing cycle.

Case Study Results

Case 1: Reduction of Cure Time Safety Margins in SMC Production

Impedance control technology was installed on a press running an SMC production part in December 2003. The part is an instrument panel for a light truck. The part typically runs on three shifts, five to seven days a week. Figure 4 shows a typical impedance signature for this part with times expressed as a percent of normal.

The impedance signature in Figure 4 is slightly different from the signature in Figure 3 due to a change in the press clamp pressure about 30% of the way through the cycle. During the system startup on this application, the proper slope to end the cure was determined empirically by identifying the time when blisters started to occur. This setting was incorporated into the rule base to maximize production yield while simultaneously assuring adequate cure. Figure 4 shows the point used by the rule base to open the press. Since December 2003, this setting has reduced the cure time by 25% on average.

Cure time safety margins are a required and standard practice for plastics molders due to inherent variability in the process and material. Without real-time feedback from the mold cavity, the manufacturer must add safety margins to prevent increased scrap and production upsets. The impedance sensing technology provided real-time feedback that facilitated a significant reduction in cure time safety margin for this application.

Case 2-1: Temperature Variation and Cure Time Reduction for an SMC Body Panel

A production evaluation of impedance sensing technology was conducted in June 2003 at an SMC automotive manufacturer. The evaluation was conducted on a production press running an automotive body panel made with polyester SMC (styrene monomers). In this application, the normal cure temperature was 300 degrees F for the lower mold section and 310 degrees F for the upper mold section. The normal cure time for this application was 105 seconds.

To determine the impact on impedance signatures caused by temperature variation, temperatures were intentionally changed ±15 degrees F from nominal. Impedance data was collected for numerous cures at each temperature. Figure 5 shows typical impedance signatures from cures at the nominal temperature, at nominal minus 15 degrees F, and at nominal plus 15 degrees F.

Evaluation of figure 5 shows that adequate cure under nominal conditions was reached at approximately 65 seconds. This represent a potential cure time reduction of 38%.

Figure 5 also shows that the impedance signature shifts to the right as the temperature is lowered. This shift reflects a slower melt and reaction rate as expected when the temperature is lowered. In this application, the rule base automatically detected the expected cure time based on the changing mold temperature. Using this algorithm, the technology determined that the time to reach adequate cure is 64 seconds at the nominal temperature. At nominal minus 15 degrees, adequate cure is reached about 13 seconds later. At nominal plus 15 degrees, adequate cure is reached approximately 15 seconds earlier.

The in-mold sensors showed the change in cure rate as the mold temperature changed. The software then automatically determined the impact of temperature variation on the optimum cure time.

Case 2-2: Using Multiple Sensors to Detect Charge Pattern Effects on SMC Flow

Three impedance sensors were installed in the body panel mold for the June 2003 trial. Figure 6 illustrates the relative locations of the sensors and charge pattern.

Numerous impedance signatures were collected using the standard charge placement. Figure 7 shows typical impedance signatures using the normal pattern. Evaluation of this impedance data indicated the SMC cured more rapidly near Sensor 1. Confirmation the SMC near Sensor 1 cured quickly was achieved by elevating the mold temperature (approximately 15°F). Under-fill occurred near Sensor 1 at the elevated temperature due to the SMC curing too rapidly. Based on this evidence, an attempt was made to equalize the cure rates by moving the charges closer to Sensor 1 (~6 inches).

Figure 8 shows the impedance signatures from a cure after the charge pattern was shifted closer to Sensor 1. The starting and gel points are closer together for the three sensors. The impedance signatures are also aligned more closely near the flat, indicating the shift in the charge pattern equalized the cure rates at the three sensor locations.

By placing sensors in multiple locations, the SMC molder was able to understand the flow of SMC through the mold and its impact on cure rate at different mold locations. The charge placement was successfully modified to more closely match the cure rates in different sections of the mold using feedback from the impedance sensors.

Case 3-1: Detecting SMC Flow Anomalies in Production Molding

In January 2004 a production trial of impedance sensing technology was conducted on a large mold requiring a high quality surface finish. Figure 9 shows impedance signatures from an initial cycle of this trial.

Referring to Figure 9, there are some irregularities seen within the first seconds of reaching full tonnage. The impedance data is erratic and indicates the material continues to flow after full tonnage has been reached. This observed behavior is unexpected since full tonnage normally indicates the SMC has stopped flowing and the material has begun to melt. In addition, the data indicates that once the material stopped flowing, it immediately began cross-linking (evidenced by the impedance data falling). There is normally a period where the SMC is allowed to completely melt to ensure the mold is filled before cross-linking starts. It is evident the cure reaction has started before material flow is complete.

Based upon indications that the SMC was not flowing well before full tonnage was reached, the press tonnage was increased and the press closure rate was slowed. Figure 10 illustrates the impedance signature collected after this process change. Examining Figure 10, it is clear the material is flowing better with more tonnage and a lower closure rate. The impedance data is rising and smooth at full tonnage, indicating material is no longer flowing, and has not reached the gel region.

In this production application, the impedance data facilitated understanding of the SMC flow properties in the production mold. This information was used to adjust the press settings for improved processing.

Case 3-2: Detecting SMC Compound Variation in Production Molding

During the January 2004 production trial described in the previous section, impedance data was collected while several formulations of SMC were molded. Two of these formulations are compared in this report and identified as Compound 1 and 2. Impedance data presented in the previous section of this report was from Compound 1.

Figure 11 illustrates the impedance data collected while molding Compound 2. Examining Compound 2's impedance signatures in Figure 11, the sensor indicates the material flowed well (no erratic jumps in the data) and completed melting approximately 25% into the normal cure time. The rapid drop in the impedance signatures after the peak indicates the material quickly transitioned from melt to a fully cured part. The part was completely cured after 70% of the normal cure time. A post inspection of the part revealed no defects.

It is useful to contrast the impedance data from Compound 1 and 2 to understand how each cures in a production environment. To accurately compare the two SMC materials it is important to minimize the effects of other process variables. To achieve that, impedance signatures were collected from each compound within 30 minutes of each other utilizing identical press settings (tonnage, closure rates, temperature settings, etc.).

Figure 12 contrasts Compound 1 and 2 impedance signatures. Figure 12 illustrates the different gel points of the two compounds. Compound 2 did not reach a gel point until well after full tonnage, while Compound 1 had already passed the gel point and was cross-linking at full tonnage. Ideally, the SMC should melt (shown on the graph by rising to a peak) after full tonnage to allow

ample time for the material to completely fill the mold. By not reaching a gel point until after full tonnage, the material tends to cure too quickly and not fill the mold.

Examining the cross-linking portion of both materials (the down slope of the impedance data), Compound 2 initiates and ends the cross-linking crisply. At the beginning of the cycle, Compound 1 slowly transitions to the cross-linking phase, while the end of the cycle shows the data slowly tapering to a flat. The end of cure for both materials is at the same time.

Although both materials reach the end of cure at identical times, Compound 2 transitioned to a gel point smoothly (i.e. the material melted and was allowed to fill the mold completely) then rapidly initiated cross-linking. Compound 1 skipped the gel period and transitioned into the entry and exit of the cross-linking phase slowly. Without a clear gel period, it is doubtful the material would consistently fill the mold every cycle without creating non-fill failures. In fact, to create more consistent parts with Compound 1 (reduce the scrap rate associated with non-fills and under-cure) requires a lower mold temperature with an extended cure time. The lower temperature would delay the cross-linking to ensure the material melts and fills the mold. The cure time would be extended to ensure the material was fully cured at this lower mold temperature before de-molding.

Case 3-3: 32% Cure Time Reduction in Production Molding

During the last phase of the January 2004 production trial, the rule base was setup to automatically detect the end of cure for Compound 2 and open the press at the optimum time. A post inspection of the 50 parts cured by using this method verified there were no defects. Figure 13 illustrates the typical impedance data collected by SmartTrac during these cycles.

Figure 13 shows detection of the end of cure at 57% of the normal cure time. An additional safety factor was added to ensure the Styrene-Styrene reaction was complete and the part was de-molded with a high gloss finish. With this added safety factor, the average cure time reduction was 32%.

Case 4: Lab Trial of Mineral Filled Phenolic

In February 2004 a lab experiment utilizing impedance sensing technology was conducted on a brake piston mold curing mineral filled phenolic. The parts were compression molded with an impedance sensor installed in the cavity side of the mold. Phenolic material was weighed, compressed, and pre-heated before placing the charge in the mold. The experiment was designed to vary the mold and pre-form temperature while collecting impedance data, to determine the correlation between impedance and rate of cure. Cure times were varied at each condition to fabricate both acceptably cured and unacceptably cured parts at each process condition. Producing acceptable and unacceptable parts at each condition was performed to correlate the impedance data to the state of cure of the finished part.

Figure 14 shows a typical impedance curve from this experiment. Figure 15 shows the phenolic impedance data overlaid with typical SMC impedance data.

As discussed in Figure 3, the correlation of impedance to SMC's physical and cure properties is well established. Figure 15 illustrates the similarity between phenolic impedance signature and that of SMC. Both signatures initially rise, which is related to increasing molecular mobility during melt for SMC. The phenolic and SMC curves reach a peak then fall to a flat. In SMC, the peak and fall have been shown to relate to the onset and continuation of the curing reaction. The flat in the SMC signature has been proven to correlate to the end of the cure process.

Figure 16 shows the effect mold temperature changes had on the phenolic impedance signature. Lowering the mold temperature slows the melt and reaction rates. Figure 16 shows that this causes the impedance curves to shift to the right, with peaks and flats occurring later in time. The change in the phenolic impedance curves with temperature are similar to the changes that occur in SMC impedance curves (see Figure 5).

Figure 17 shows the effect pre-form temperature changes had on the phenolic impedance signature. As the pre-form temperature rose, the starting point of the impedance signature rose, indicating the sensor was detecting the additional thermal energy and increased molecular mobility in the material. The time of the peaks shifted to later times as the pre-form temperature was lowered. It also took longer for the impedance signature to reach a flat as the temperature was lowered.

Figure 18 compares the impedance signatures of representative parts cured at different conditions with different cure properties at the time the press opened. The part in which the press opened just after reaching an impedance peak had a large blister due to under cure. A part in which the press opened about forty seconds after the peak but before the curve reached a flat had porosity due to under cure. The part in which the press opened at the time the impedance had reached a flat showed no cure related defects. As with SMC, the impedance data in Figure 18 indicates the flat portion of the impedance

curve correlates to adequate cure to prevent porosity and blisters in the part.

Examination of Figures 16, 17 and 18 shows that the impedance data has a strong correlation to the rate and state of cure for a mineral filled phenolic.

Summary

Impedance sensing technology presents a new mechanism to obtain real-time feedback from the production molding environment. The technology detects changes in dielectric properties related to cure state, allowing it to identify the optimum time to end the cure cycle.

Production and lab trials of SMC and phenolic presented in the paper demonstrate that implementation of the technology allows the manufacturer to:

- Reduce cure times by eliminating much of the cure time safety margin currently used to account for process variability.
- Automatically detect and account for process and material variations.
- Identify charge placement and material flow discrepancies and adjust settings to improve the process.
- Identify the impact of different compound formulations on material flow and cure rate.

Figure – 1: Capacitor Formed by Mold-Sensor Arrangement

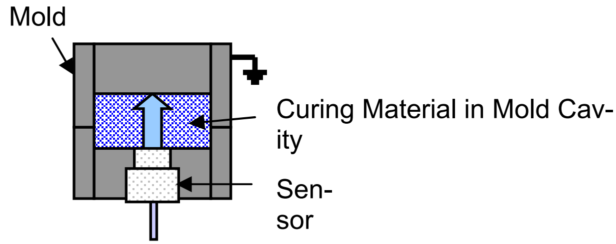


Figure – 2: Impedance Sensor Physical Layout

Figure – 3: Typical SMC Impedance Signature

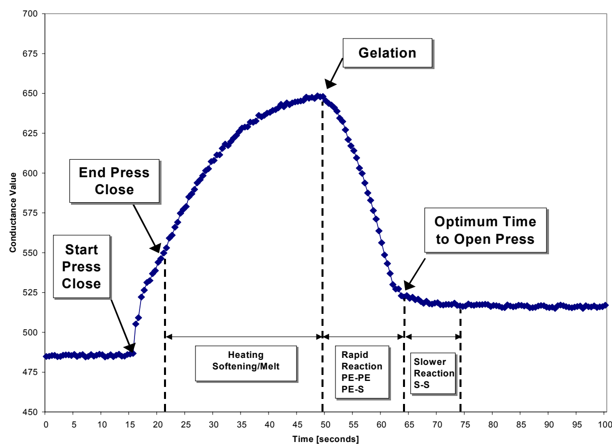


Figure – 4: Impedance Data - SMC Body Panel

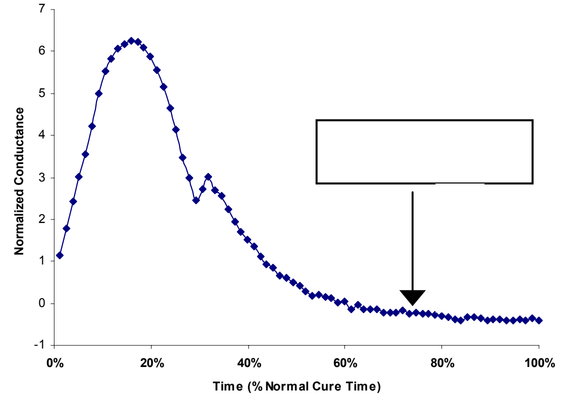


Figure – 5: Changes in Impedance Data with Temperature Variation

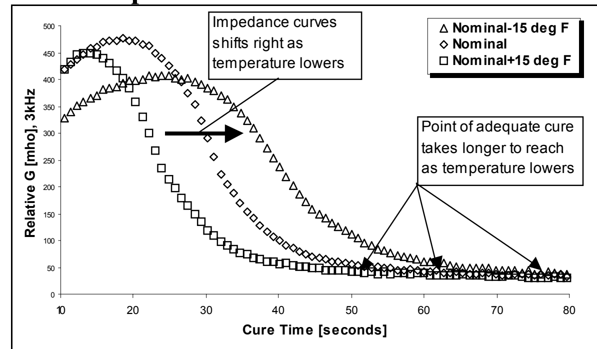


Figure - 6: Relative Locations of Sensors and Charge Pattern

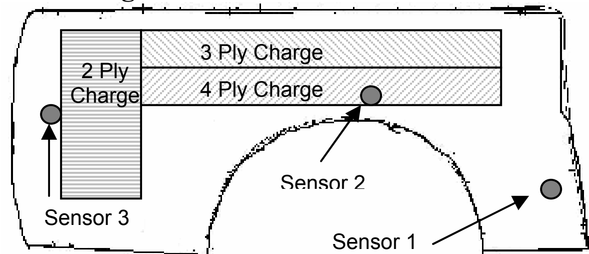


Figure - 7: Impedance signatures show mismatch in cure rates

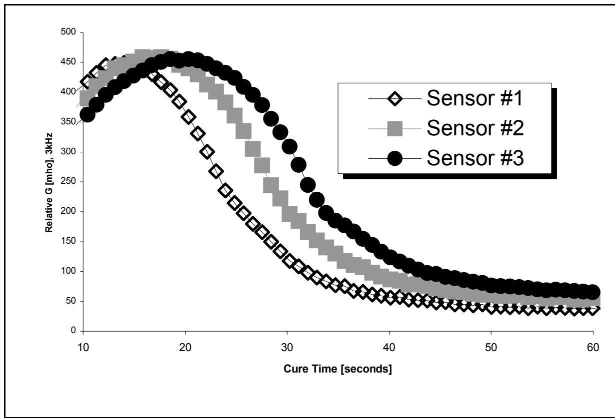


Figure - 8: Impedance signatures matched after charge pattern shifted

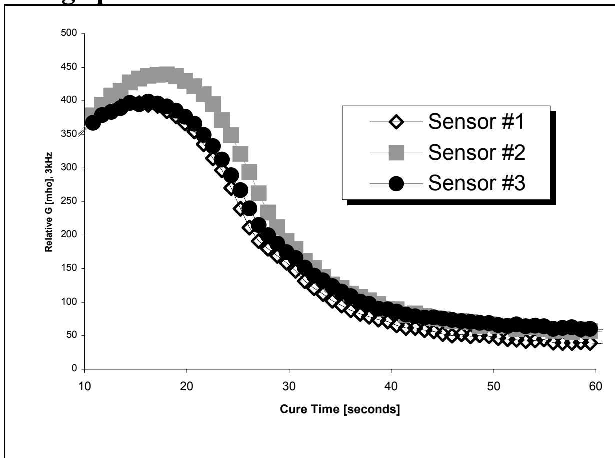


Figure - 9: Impedance Signature Showing Poor SMC Flow

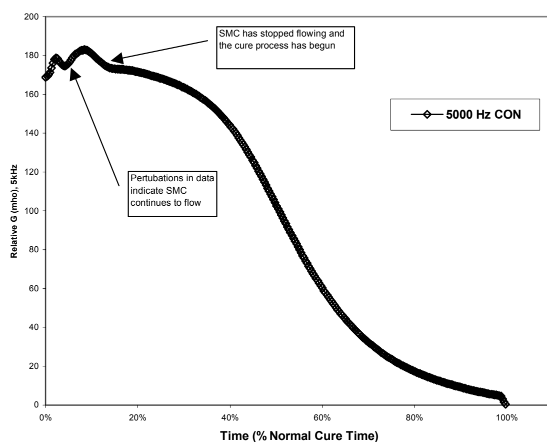


Figure - 10: Impedance Signature with Improved SMC Flow

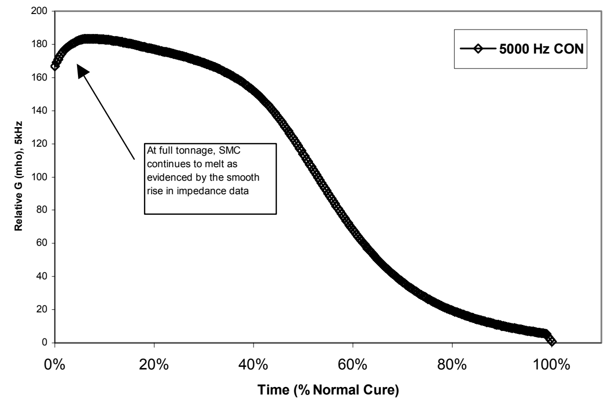


Figure - 11: Compound 2 Impedance Signatures

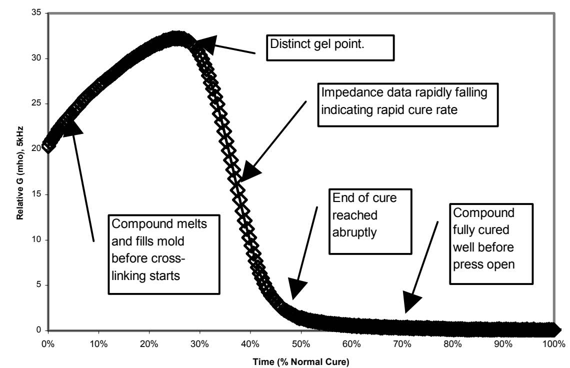


Figure - 12: Comparison of Compound 1 and 2 Impedance Data

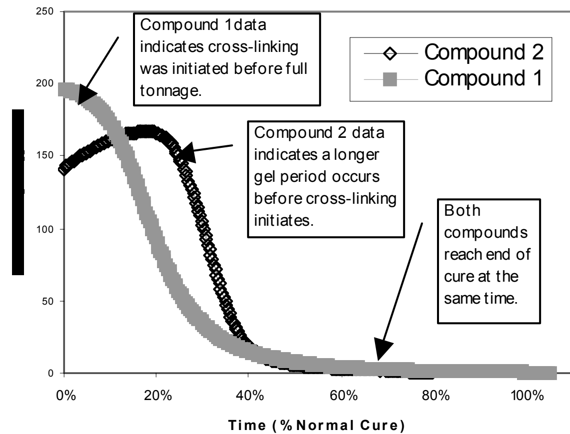


Figure - 13: 32% Reduction in Cure Time

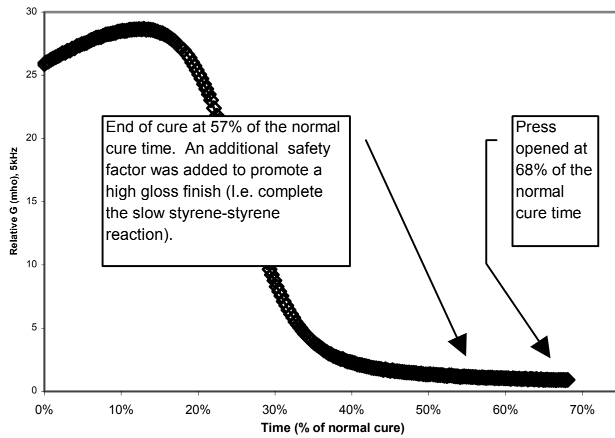


Figure - 14: Typical Phenolic Impedance Signature

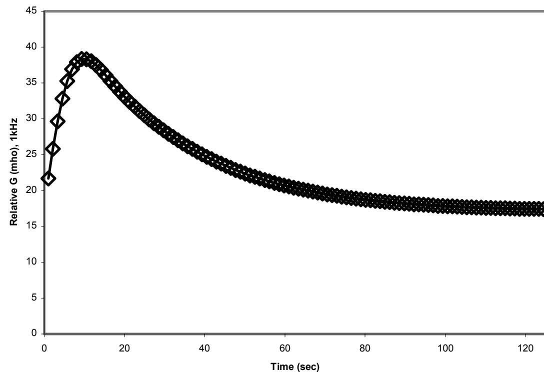


Figure - 15: Comparison of Phenolic and SMC Signatures

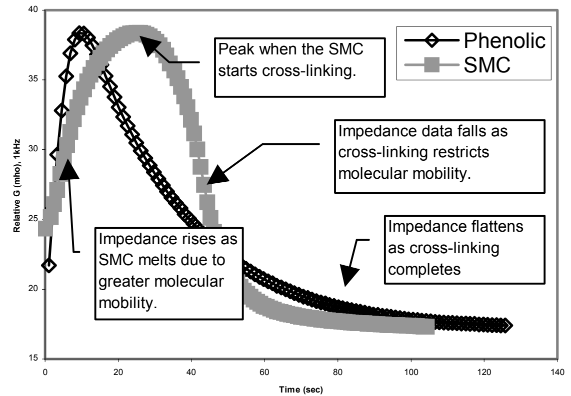


Figure - 16: Change in Phenolic Impedance with Mold Temperature

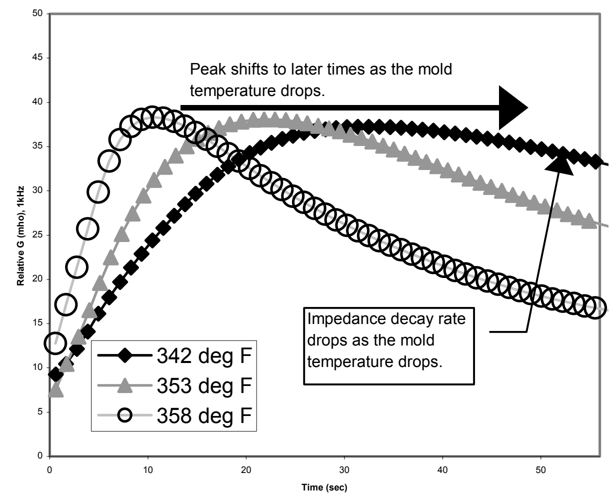


Figure - 17: Change in Phenolic Impedance with Pre-Form Temperature

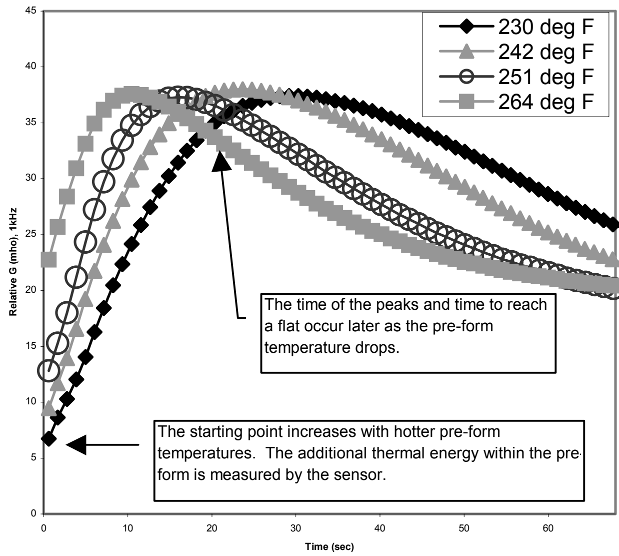
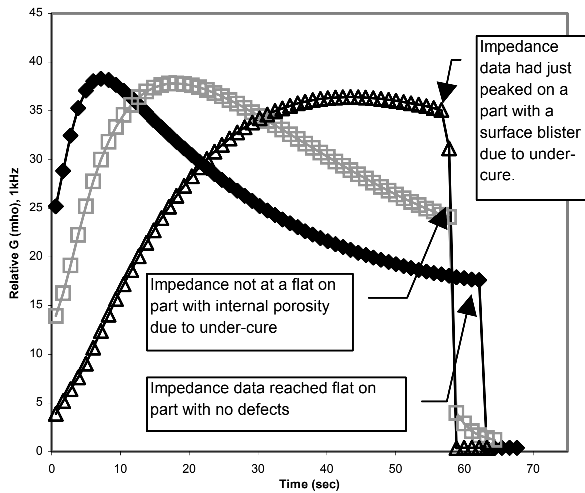


Figure - 18: Relationship between Impedance and Cure State for Phenolic



Author:

Steve Courington,
Director of Operations,
Signature Control Systems.
Steve has a B.S. Materials Science from Rice University and 12 years experience in industrial automation.