Real Time Production Process Control For the Composites Industry

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Abstract

Impedance sensing technology provides a method for thermoset molders to monitor 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 thermoset injection and compression applications as well as some results from a few production installations. Data discussed in this paper will show that impedance sensing technology:

- Can be applied to most thermoset injection and compression applications
- Is easy to implement on production presses and into production molds.
- Detects the effects of mold temperature changes on cure rate in the production mold.
- Automatically adjusts cure times to compensate for mold temperature fluctuations.
- Provides valuable feedback on the molding process that can assist in troubleshooting and continuous improvement efforts.
- Can be used to identify material variation
- Improves productivity
- Relieves molding constraints, which enables a company to focus and eliminate other constraints.

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 hundreds of 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. This ceramic face permits use of the technology with conductive materials by preventing the sensor from "shorting" as was the case with previous impedance sensing technology.
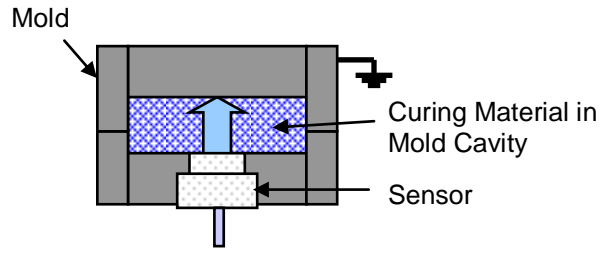
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Figure 1: Capacitor Formed by Mold-Sensor Arrangement
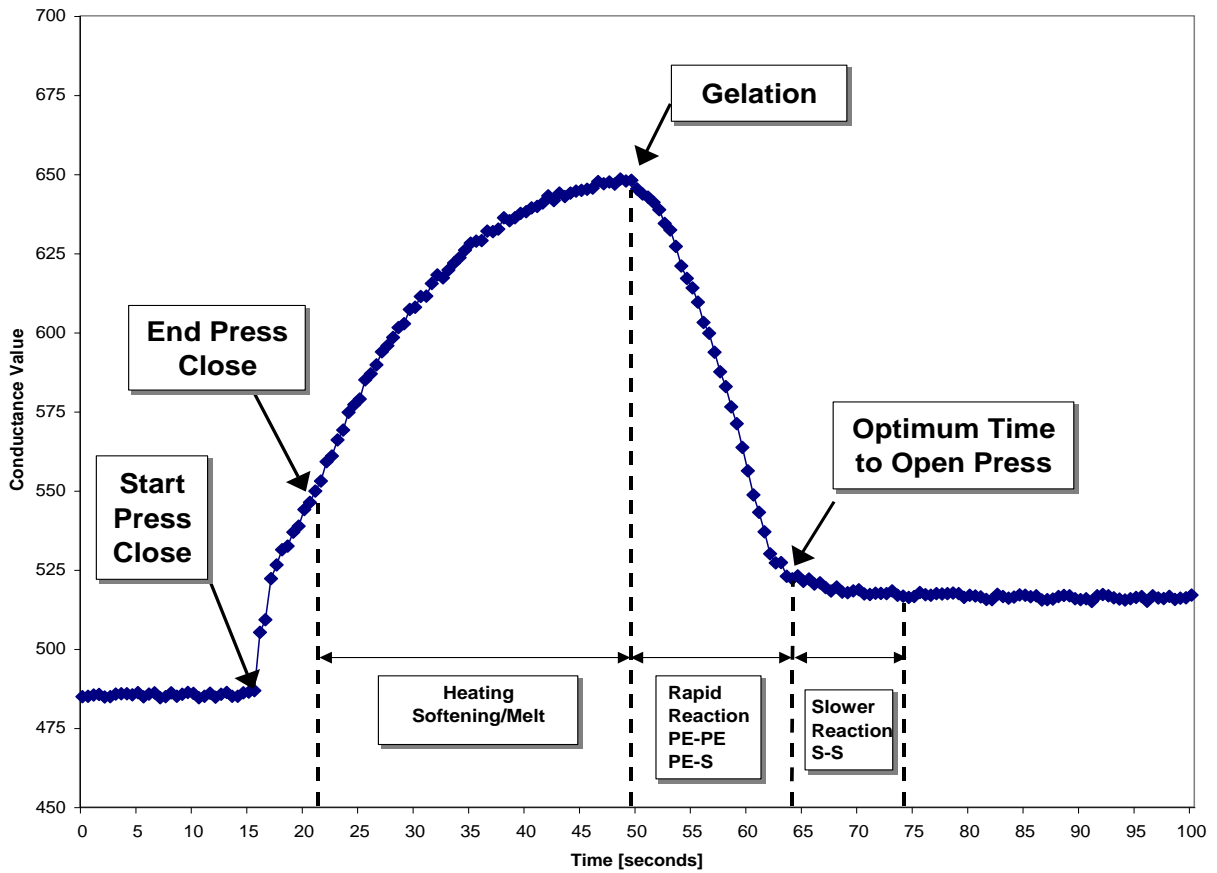

Figure 2: Impedance Sensor Physical Layout

Figure 3: Typical SMC Impedance Signature

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

Implementation consists of four main activities; selection of the part, sensor placement, press programming and rule base development.

Part I – Part Selection

When selecting a part for dielectric cure control, decisions are made based on both financial and technical concerns. The two main benefits of the technology on the production floor are improved part quality and increased productivity. Parts with quality problems, high scrap and the potential for costly litigation are logical applications for the technology. Where manufacturing efficiency is concerned, selecting a part where the press is the bottleneck of the operation will translate directly to hard savings once the technology is implemented. Significant consideration should be given to high volume parts & high value parts. However, if cure control technology is implemented upfront with the original built of molds for new products, cost is significantly reduced.

The type of material that is used for the given application should be a minor factor when selecting a part. Whether simply monitoring the process or controlling actual production cure times, impedance sensors can be used in virtually every thermosetting process and with virtually every thermosetting material. SMC, BMC, epoxy, urethane, urea, melamine and phenolic have all been tested successfully. Unique materials can be tested in a laboratory to determine the strength of the signal and the features of the cure curve.

Part II – Number of Location of Sensors

Many factors should be considered when choosing the number of sensors to install in the mold as well as the location of those sensors.

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How many cavities are there in the mold?

The maximum number of sensors that can be installed in any mold is four (4). With large parts and multi-cavity tools, the number of sensors should depend on the end use of the part and the current level of process control. For parts used in critical applications, the molder may want to locate as many sensors as possible to maximize process control across the mold. In this multi-sensor scenario, SmartTrac is programmed to keep the press closed until all sensors indicate that the material has reached optimum cure. If the existing level of process control is thought to be inadequate, additional sensors should be installed in order to account for this variation that can adversely affect part quality and performance.

Is the part compression or injection molded?

With injection-molded parts, there are a number of options for sensor location. The sensors may be located on the part, directly in the runner or in a "witness" cavity off of the runner or part as seen in Figure 4. Placing the sensor in a witness cavity also gives the engineer the flexibility to use an adjustable core pin design that enables the thickness of the cavity to be varied. By varying the thickness of the witness cavity, the molder can mimic the cure rate of a particular area of interest in a thicker or thinner area of the part. If the part is compression molded, often the only option is to place the sensor in direct contact with the part.
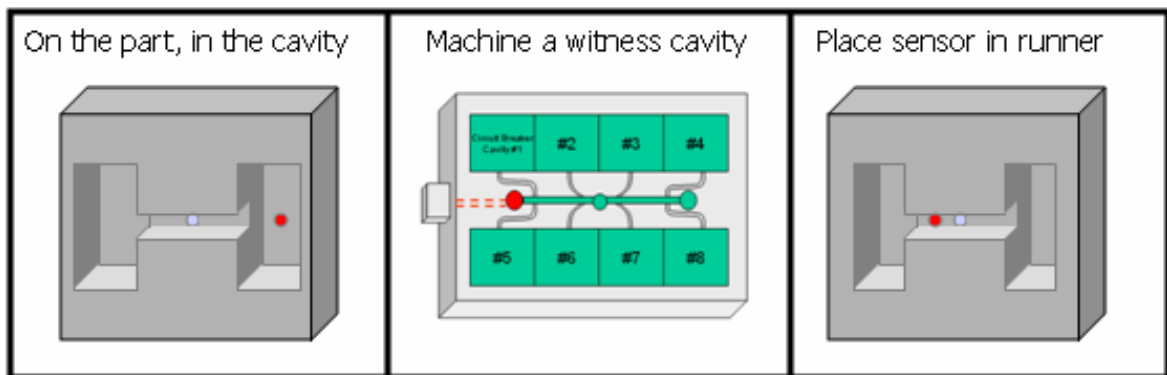

Figure 4: Options for sensor placement

Is there a flat area on the part large enough to accommodate a sensor?

The face of the in-mold impedance sensor that is in direct contact with the curing material is 14 millimeters in diameter. In order to obtain a usable signal, the material must cover the majority of the sensor. Some parts are too small to place the sensor on the part. In this situation, the engineer may locate the sensor in the runner (if injection molded) or they may convert an existing cavity into a "witness" cavity. When converting a part cavity to a "witness" cavity, the engineer must understand the cost-benefit trade-off of eliminating a cavity and sorting out the "witness" pad. The other option in both compression and injection processes is to "build-up" a flat area on an existing contoured surface to permit sufficient sensor coverage.

How many heat zones are there in the mold?

The greater the number of heat zones the better equipped the molder is to control the temperature throughout the mold. At the same time, this also increases the chances that the heat source in one area of the mold could fail. For this reason, the molder may want to install a sensor in every heat zone to maximize process control. Fortunately, the reliability of most common heating systems: steam, electric and hot oil, has increased dramatically over the years. Thus, the number of heat zones in a mold is generally not included in the final decision for sensor location or number of sensors used.

Are there any problems areas of the part?

If the cause of the defect is cure-related, the impedance sensor will be able to monitor the cure rate of the material in that location and make the appropriate adjustments to the cure time to ensure that the part is adequately cured. If it is known that there are particular areas of the mold or cavities that are prone to defects, then that area would be a logical location for a sensor.

Should I place a sensor at the last place to cure?

Intuitively, it makes sense to locate the sensors in the last place to cure (coldest or thickest area of the part). Practically speaking, the best place to locate the sensor is on a nominal thickness section of the part. Then, it is a simple matter of establishing the relationship between the cure state of the part where the sensor is located to the "lagging" area of the part. This relationship remains very constant.

Where are the cartridge heaters, heat pipes, ejector pins and other sensors located?

Knowing the location of other hardware in the mold is extremely important when choosing sensor locations. Use the prints and position the sensor(s) in a place where the tool shop can drill the sensor hole without hitting anything else in the mold. For this reason, it is best to incorporate the sensors into the mold during the design phase when the sensors can be placed in the ideal location without restrictions.

Is a sensor mark on either surface objectionable?

Per Figure 5, the sensor is installed perpendicular and flush with the surface of the mold. It is slip fit, not press fit. As a result, the sensor will leave a witness mark on the part similar to that made by an ejector pin. If this is objectionable to the customer, then the best solution is to locate the sensor(s) in the runner, on a "non-show" area of the part or on an area of the part that is cut out downstream.
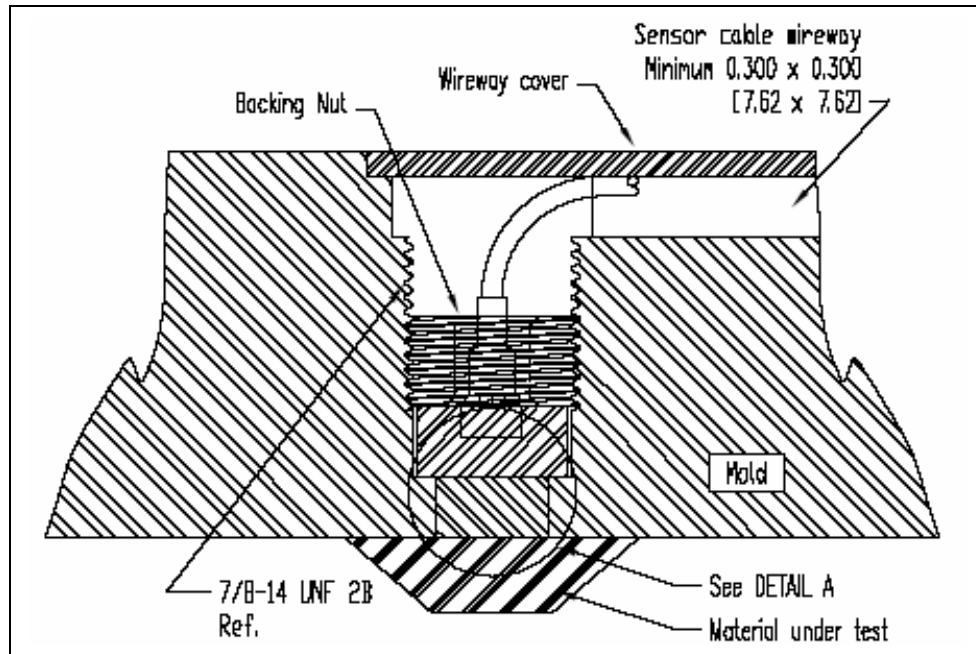
Figure 5: Installation of impedance sensor

Part III – Press Programming

The impedance sensors are connected to a computer controller with signal conditioning and data acquisition 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. This normally occurs at the end of injection, retraction of the plunger or when full tonnage has been achieved. The controller then turns on the sensor voltage and begins monitoring the impedance signal when this signal is received from the press. Operating in parallel with the existing press control system, the controller acts as the cure timer when in "control" mode. The controller is also wired to signal the press to open instead of the normal cure timer. When the system detects that the optimum slope (optimum cure state) has been reached, it sends an output signal to the press control system to override the fixed cure timer and automatically open the press.

Often, the molder has the in-house expertise to complete the necessary press programming. In the event that this expertise is not available or the press control system is governed by proprietary software that cannot easily be changed, SCS will work with the molder, the manufacturer of the press control system and the press manufacturers to make the necessary press programming changes to ensure reliable and accurate communication.

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Part IV – Rule Base Development

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.
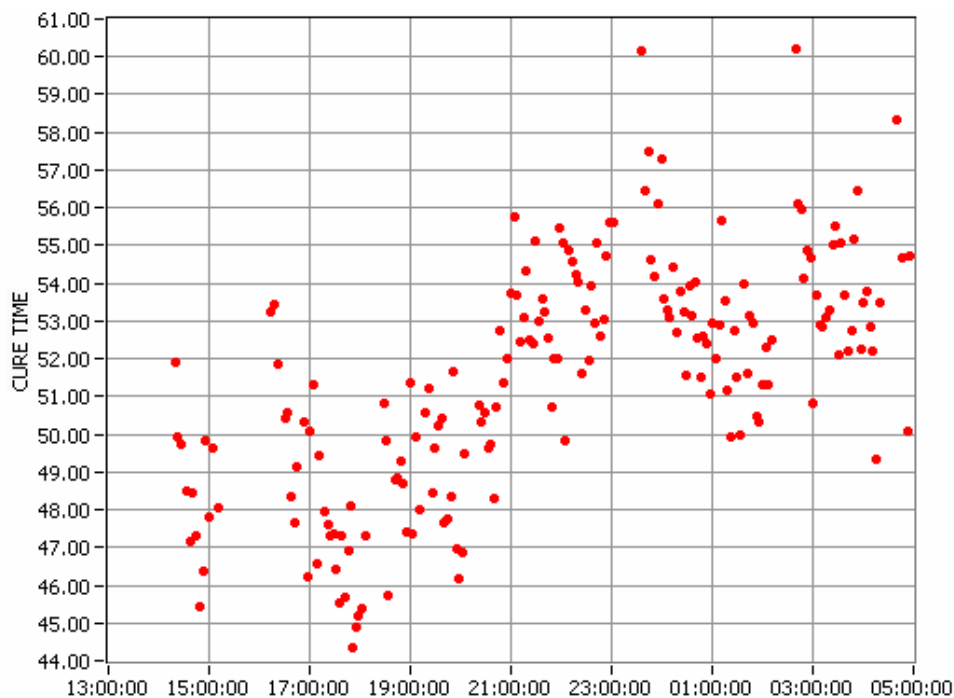

Figure 6: Shift to shift variation

Case Study Results

Case 1: Detecting and adjusting for shift-to-shift operator-induced variation in a compression SMC process

Impedance sensors were installed in a SMC compression mold to reduce cure times and improve process control. Figure 6 shows the average cure times during the 2nd and 3rd shifts. It was observed that the average cure times increased by approximately 5 seconds when the 3rd shift crew took over the production of the parts. The data was reviewed with the shift supervisors the next morning. There were no differences in the press parameters or mold temperatures to explain the shift in cure times. It was confirmed that the parts at the end of the 2nd shift and beginning of the 3rd shift were all made from the same batch of material as well. The same phenomenon was observed every night for the next 5 days. Upon closer investigation, it was

determined that the 3rd shift press operators took particular care in cleaning debris out the mold between cycles. They were using the plant forced air to blow leftover glass and other potential contaminants out of the mold. The difference was that they routinely directed the air on the mold surface for 5-10 seconds longer than the 2nd shift operators. The additional air cooled the mold surface by an average of 2-3 degrees and caused the parts to cure at a slower rate due to the slightly lower mold temperature. The impedance sensors detected this change in cure rate and provided the engineers with the necessary data to identify an assignable cause of the variation.
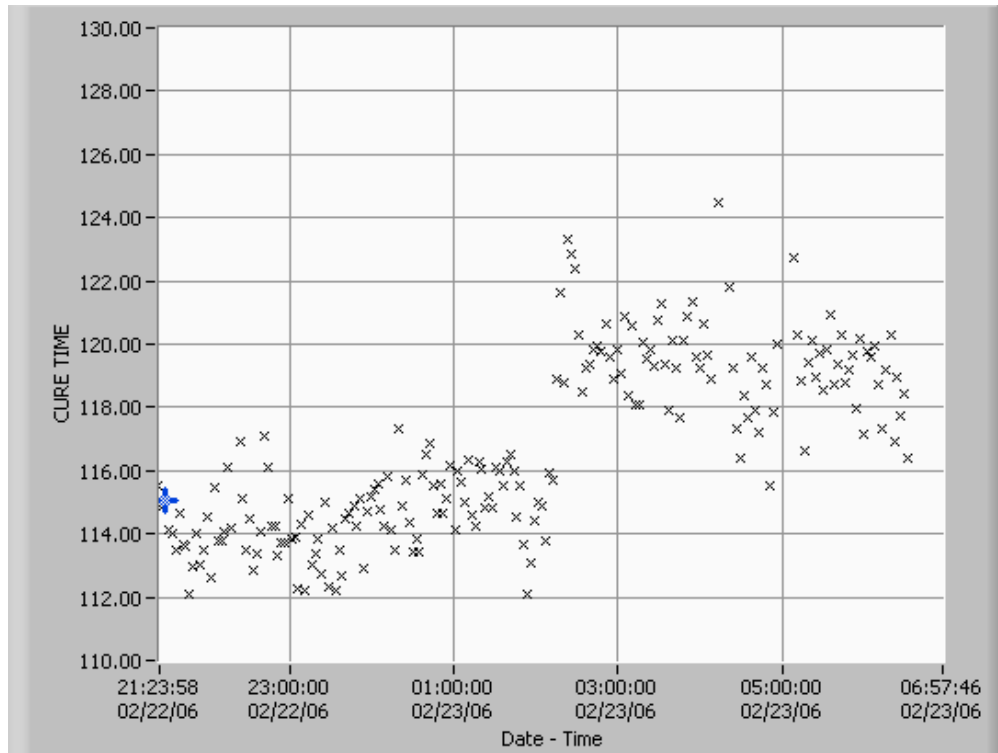

Figure 7: Batch to Batch material variation

Case 2: Reducing cure time and detecting batch to batch variation

One impedance sensor was installed in a two-cavity injection BMC industrial circuit breaker mold. The fixed cure time prior to installation was 142 seconds. A rule base was developed and parts were tested to validate the set slope for cure control. Figure 7 is a run chart showing 357 cycles run over a 20-hour period. The average optimum cure time with SmartTrac in control of the process was 116.5 seconds. This represents a 19% reduction in cure time. While looking at the run chart, it was observed that a process shift occurred around 2 am. Upon further investigation, it was determined that the shift was due to a batch change. The last batch of material had an average cure time of 119.4 seconds or a 3 second increase. The impedance sensors detected the difference and made the appropriate adjustments in cure time to produce consistent parts in the minimum amount of time. The impedance data was used to identify the assignable cause of variation.

Case 3: Press open or press closed during production interruptions?

Impedance sensors were installed in two separate compression molded BMC applications at two different companies. During production interruptions, the companies had different procedures for locking out the press during the breaks (lunch, breaks, shift changes, etc…). The procedure for company A required the operators to leave the press open while the guidelines for company B called for the operators to close the press during breaks. Figure 8 shows a typical run chart for company A. Because the mold was left open, the press cooled down. Due to the colder mold, the first cycle after the break was significantly slower than the other cycles and it took 5-10 cycles for the press temperature and the process to stabilize. Figure 9 shows a typical run chart for company B. As a result of keeping the press closed with no material running through, the mold had an opportunity to heat up. When the operators were ready to begin production again, the mold was the hottest that it gets. The hotter mold temperatures produced the fastest cure times. Again, it took a number of cycles for the process to stabilize.
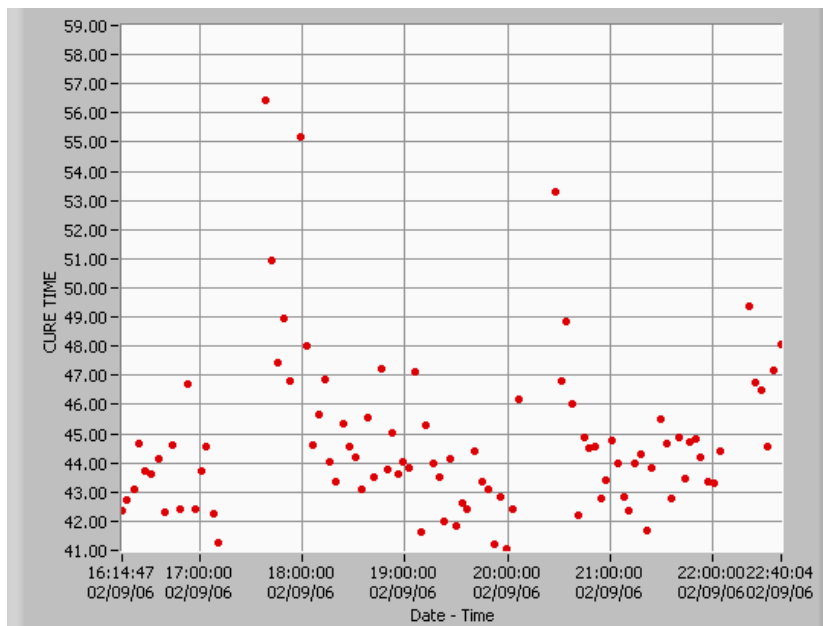

Figure 8: Cure times increase when mold is left open during breaks
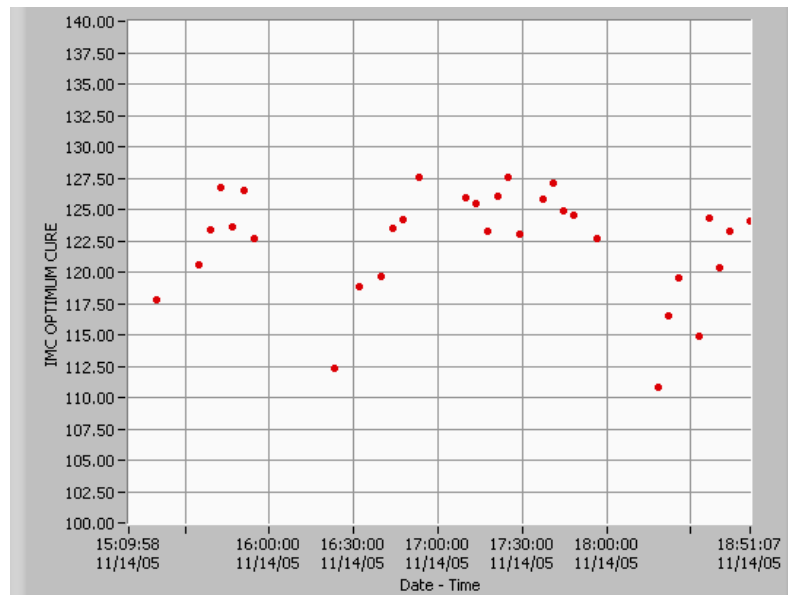
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Figure 9: Cure times decrease when the mold is closed during breaks

Summary

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

When implementing the technology, the molder should follow a couple of guidelines:

- Any thermoset part is a good candidate for production dielectric cure control.
- Payback will be quickest on high volume parts, parts that are high value and parts with quality prob-lems.
- Sensors can be placed on the part, in a witness cavity off of the runner or directly in the runner itself
- Sensors are typically placed in an area where the cross-section thickness in nominal

The sensors can be used to:

- Increase productivity
- Improve quality
- Improve engineering efficiency by providing meaningful feedback on the process
- Reduce scrap
- Increase machine utilization

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