Practical Applications of Process Control in Conformal Coating

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Abstract
The development of automated selective coating systems was the first step in improving the conformal coating process. Variables in the process can cause defects if not detected and compensated. Process controls integrated into the automated system reduce the variations and ultimately the defects. This paper describes the systems, sources of variations, and controls to compensate for those variations.

Introduction
Conformal coatings protect electronic products from solvents, moisture, dust, or other contaminants that may damage them. Coating also prevents dendrite growth, or oxides growing on the Printed Circuit Board (PCB). Dendrite growth can create short circuits and result in product failure. A variety of techniques for applying conformal coatings to products are used in the electronic industry. Like most manufacturing processes, conformal coating application methods have evolved from manual to automated systems.

Non-Automated Coating Processes
One of the oldest and best-known methods of coating is the dip process. In the manual dip operation, operators immerse the PCB in a tank of coating. Components on the PCB that cannot be exposed to coating must first be masked. Tape is manually applied prior to coating. The masking is then removed after the board is cured. Masking is labor intensive and involves consumables, making the process inherently wasteful. Some dip systems automatically move the board in and out of the tank, allowing for better repeatability. Although dip systems are simple and involve a low capital investment, the variation in coating thickness, contamination issues, viscosity variations, manual masking, cleanliness and operator comfort and exposure make this a crude process with little control.

Brushing the material on the PCB is another method used to conformally coat a PCB. This is typically a manual process in which an operator dips a brush into a container of coating material, and then brushes the material onto the PCB. There is little investment in equipment or tooling and the process is simple, but crude. Brushing introduces the same problems associated with the dip process. Although brushing may be adequate for low volume prototype runs, this process is not viable for mass production.

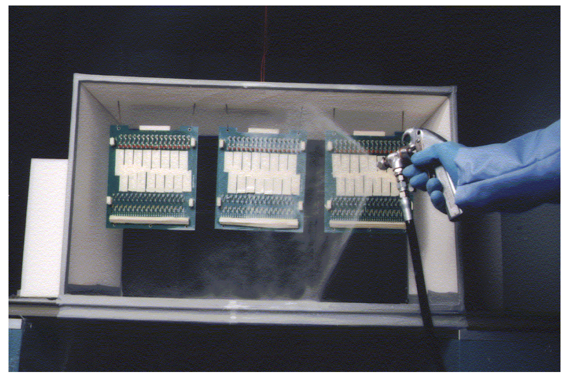

Figure 1. Manually Air-Spraying Coating

Manually air-spraying the board is another common method for applying a thin film of conformal coating material to a PCB (Figure 1). Since air-spraying produces a large amount of overspray (wasted material), hand masking is required beforehand. After the masking is complete, the boards are laid out or hung in a spray booth. An operator sprays the PCB's with a hand-held spray gun similar to those used to spray paint. Once the boards are cured, the masking material is removed. The operator is continuously exposed to the coating during and after the process, which can create safety and health issues. The coating thickness and consistency is operator-dependent and not highly repeatable.

The introduction of needle dispensing, which can be done manually or robotically, applies coatings in smaller volumes. The coating material is forced through a needle and is dispensed as a bead. Beads of material are placed in different locations on the board and through capillary action produce the desired coverage. The manual needle dispensing equipment cost is low, but is operator-dependent and not highly repeatable. Automated needle dispense systems increase repeatability, but fast coverage and dispenser robustness are difficult to achieve.

Selective Conformal Coating
Major improvements in the conformal coating process can be realized through the use of automated

systems that selectively apply coating. A dispenser mounted to a robot is programmed to move and dispense material in designated locations on the PCB. The systems are either designed to manually load boards or equipped with conveyors for in-line board processing. The coating material, dispenser type, and robot speed determine the coverage and film build. Selective conformal coating machines provide a consistent application of material, higher throughput, material savings, closed fluid systems, and with the proper dispenser and PCB layout, do not require custom tooling or board masking. The main disadvantage is the cost of a selective conformal coating machine compared to other methods.

Systems

Selective conformal coating systems consist of a workcell, curing module, and possibly board handling equipment (Figure 2). The product coating takes place in the workcell. The workcell can be an in-line system with a conveyor that moves boards in and out or a stand-alone system, where boards are inserted and removed manually. It consists of a software-controlled robot, coating area, and fluid system. The operator programs the coating routine into the system computer, where multiple programs are stored for the different products. In a stand-alone system the work area is typically a tooling plate that holds the board in place. The work area in the in-line system uses a pin or clamp on the conveyor to stop the board at a desired location for coating. The fluid system is pressurized and controlled to attain a desired flow rate. A fluid system typically consists of a pressure pot, fluid filter, and fluid regulator. Some systems use a recirculating, temperature-controlled fluid system. The curing module depends on the coating material. The various forms of cure are heat (infrared or convection), ultraviolet (UV), and humidity. The curing module is in the form of an oven with an integral conveyor for in-line systems. If two sides of the board need to be coated in an in-line system, a board flipper may be used to invert the board.

Figure 2. In-Line Conformal Coating System

Coating Dispensing

Conformal coating dispensers can be classified into atomized or non-atomized deposition. Non-atomizing dispensers can be in the form of a needle dispenser or film coater. A needle dispenser applies the coating in a narrow, thick band and is useful for small areas. However, a needle will tend to drip, since the shut-off point is far from the tip. Dripping will cause problems if the coating lands on a connector or other undesirable location. Film coating is achieved by dispensing pressurized material through a crosscut nozzle. This technique results in a leaf-shaped pattern of material (Figure 3). Film coating is most effective when the material viscosity is less than 150 centipoises (cp). Film thickness of .025 - .20 mm (.001 - .008 in.) is easily attainable with a repeatable, sharp edge definition. The shut-off point is close to the nozzle, which limits dripping.

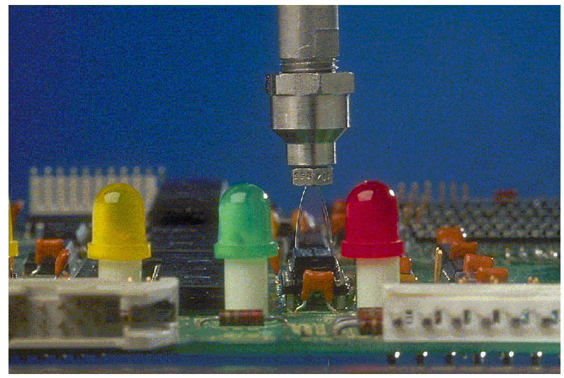

Figure 3. Non-Atomized Film Coater

Air-spray technology is an example of an atomization process. During atomization some droplets will drift when breaking the material into fine particles. Most particles in the center of the pattern land in the desired area, but a certain percentage of particles land outside. The result is a non-uniform or ragged edge, which may not be acceptable. If a sharp edge is needed, a secondary pass with a bead or line dispense might be required. Some atomized patterns are better than others. Transfer efficiency, the amount of coating that reaches the board, is typically 70-80 percent. This means 20-30 percent is overspray that goes to waste. If the air is mixed with the fluid inside the dispenser the material can wick into the cavity, requiring it to be cleaned frequently. Dispensers with externally mixed air require less cleaning and produce a controlled atomization pattern, minimizing overspray.

One method of attaining a controlled, atomized spray pattern is in a tri-mode conformal coating dispenser (Figure 4). The three modes are bead, monofilament, and swirl (atomized pattern). The bead mode performs the function of a needle dispense without the dripping. As an external swirling pattern of air is introduced around the bead via software control, two separate dispense modes are possible: monofilament and swirl spray modes. In monofilament mode, the assist (shaping) air spins a single strand of material as it exits the nozzle. As the material stream spins away from the nozzle, it stretches into a conical-shaped looping pattern, which flows together on the board. Swirl spray occurs when the assist air pressure and velocity are increased, causing the material to atomize into a swirling, conical pattern. Not only does the tri-mode dispenser provide a controlled, atomized pattern it also allows for flexibility of different dispensing types.

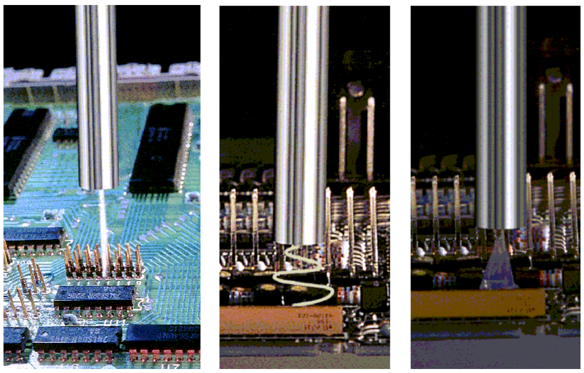

Figure 4. Tri-Mode Conformal Coating Dispenser

Benefits of Selective Conformal Coating

All manufacturers who have switched from the messier manual or older dispensing methods to selective conformal coating can attest to its benefits. The flexibility, cost savings, and additional process controls of a selective coating system are improvements over the older coating processes. Since the robot is programmable, the system can be programmed for different boards and each program can be stored in memory. Programs can be easily modified, adding to the system flexibility. Reduced material usage from spray and dip applications and reduced ventilation and energy costs create savings. Since masking is virtually eliminated the cost of coating masking material is saved. Workcells typically require less ventilation than spray and dip booths, so smaller ventilation motors that use less electricity can be used (Table 1). A major benefit with selective conformal coating systems is in the introduction of process controls. Costs associated with scrap or reworked boards can be great. Process controls are easily integrated in the existing system computer and monitor the process, thereby reducing coating errors.

Knowledge of the sources of the process variations is important in developing controls. The following will discuss the sources of conformal coating process variation, methods of control, and some practical applications of process control.

Table 1. Cost Savings with Selective Conformal Coating

Parameter	Typical Spray Booth	Selective Conformal Coating System
Annual Material Usage (gal.)	104	43
Material Cost ($/gal.)	$100	$100
Annual Fluid Cost	$10,390	$4,284
Ventilation:		
Opening Area (ft^2)	20	6
Flow (ft^3/min)	2000	600
Power (kW)	1.2	0.4
Annual Electrical Cost	$869	$261
Total Operating Cost	**$11,259**	**$4,545**
Annual Savings		**$6,713**

Process Variation

Every process has some variation. The amount of normal or acceptable variation will depend on the process. For example, when dispensing ketchup on a hamburger one might live with 12 grams plus or minus 6 grams (50 percent) variation from one hamburger to another. However, when dispensing surface mount adhesive on a circuit board the tolerance will be much tighter (5-10 percent). Therefore, the variation needs to be defined statistically and limits must be set for allowable variation of the process. Process variation will be investigated by identifying the sources, defining the normal limits, and the reviewing the effects on the end product.

Sources of Variation

The sources of conformal coating process variation can be classified into fluid properties, system air, dispenser nozzle fouling (blockage), and board surface tension (Figure 5). The main cause of variation is coating fluid properties. The fluid flow through a conformal coating nozzle is controlled by pressure and viscosity. The viscosity depends on the temperature, material properties, mixture of solvent (for materials other than 100% solids), and time. The viscosity of all fluids will vary with temperature. When the temperature in a manufacturing plant increases, the coating viscosity typically decreases, thereby creating more flow. The amount of variation depends on the fluid. Also, the viscosity range of available coating materials is 10-1000 cp. When a fluid is changed, the process needs to be corrected for this change. For materials that require a solvent to be mixed with the coating the ratio of solvent-to-coating will affect the viscosity. If the mixture is not consistent from one batch to the next, the viscosity will not be consistent. Time can be a destabilizing factor with coating materials. Some fluid will thicken over time, especially if exposed to air in a pressure pot. Some materials, that are sensitive to environmental factors such as moisture cure silicones, are contained in sealed bags to prevent the material changing viscosity, or worse, curing in the container.

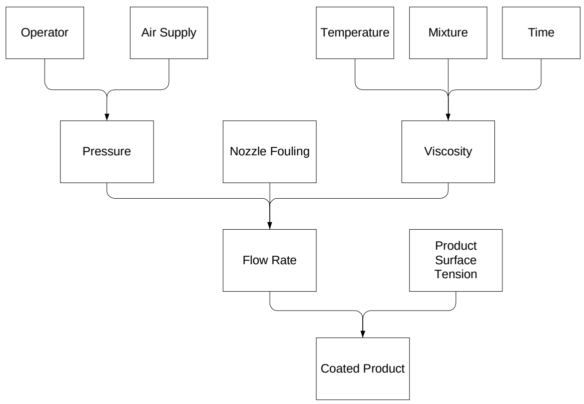

Figure 5. Flowchart for Sources of Coating Variation

The compressed air supply to the workcell can be another source for coating variation. Since an air pressure regulator controls the fluid pressure, which in turn controls the flow, variations in air pressure to the fluid regulator will cause variation in coating. Typically regulators control pressure well, although mechanical regulators have been known to drift slightly. The drift is usually minimal but if trying to regulate at an extreme of the unit (low or high) the drift can be significant. In many cases different operators will adjust the fluid pressure, some to compensate for viscosity changes, others because they like to tweak knobs. Either way the flow can vary during a production run. In some instances humidity/water or oil in the air supply line can mix with the coating. This is detrimental to any coating process. The contaminant can cause defects on the board. Filtration on the workcell's inlet air supply is mandatory to prevent this.

Since conformal coating is a material that is intended to cure and harden, coating residue left on the dispenser nozzle can cause it to foul. The coating disrupts or blocks the flow of coating. The result is coating going to undesired locations or no coating on the board. Left undetected, many boards can go through an in-line system with defects. Parking the dispenser nozzle in solvent when not being used and/or utilizing an automated brush box will reduce the chance of fouling.

The surface tension of the Printed Circuit Board (PCB) defines how much the coating will flow after it is dispensed. All coatings flow after being dispensed, but the extent of flow is quantified during the initial programming. If some boards are cleaner than others, the degree of flow will also vary. Clean boards have a lower surface tension and allow more flow. If all the boards have the same surface tension, the flow will be consistent. In some cases a plasma system will be used to clean the boards or product to ensure a consistent surface tension and ensure good adhesion. In most cases, though, this is not necessary. Surface tension is not easy to control in process and is usually not compensated.

Defining the Limits

Now that the sources of variation have been defined, some methods of defining the limits can be discussed. Typically, conformal coating dispensing does not need to be as precise as other fluid dispensing in electronics, such as underfill. The question is how good is good enough? The answer depends on the customer and application. A method used to track the process statistically is a control chart. A desired amount is the target value. The manufacturing engineer will set the upper specification limit (USL) and lower specification limit (LSL) based on the acceptance criteria of the product. When actually recording the data, control limits are used to statistically evaluate the data and process. The mean value (y_{ave}) for a particular product is determined by averaging a group of samples (10-25) or by taking a running average. The standard deviation of those samples is used to define the upper and lower control limits. By setting the upper (UCL) and lower (LCL) control limits to ± 3 standard deviations or 3σ, 99.7 percent of the values should fall into this range. The control limits are calculated using the formulas below.

$UCL = y_{ave} + 3\sigma$
$LCL = y_{ave} - 3\sigma$

Whether the system is measuring the volume of material dispensed or the width of the spray pattern, the values can be averaged and the standard deviation calculated. By setting limits, the process can be monitored to determine if not enough or too much coating is being put on the board. It will also tell the operator if the process is approaching one of the limits. This would indicate a gradual change, and something needs to be corrected. Also, a sudden jump out of the limits can indicate a nozzle clog or other problem with the system. The control limits should be within the process specification limits. Examples of limits are discussed in the Case Studies and Applications section.

End Product Effects

So what happens if a system has no process control? If there are no variations in the process, nothing bad happens. But Murphy's Law states: "Whatever can go wrong, will." In many plants it may be sufficient for an operator to monitor the system while it is coating. If the operator takes a break or is trying to monitor too many things, especially in a high volume plant, a mass of defective boards can be produced. The other factor to consider is maintenance. If a nozzle partially blocks with cured coating, material flow is reduced, but the spray can go to the side spraying all over the workcell, creating a clean up mess and downtime. Next, the process controls available in selective conformal coating to avoid these problems will be reviewed.

Conformal Coating Process Controls

Process control consists of software and equipment that automate and monitor the process. The software allows the operator or manufacturing engineer to interface with the coating process and alert the operators to problems when they occur. Process control components monitor and control the dispensing process and fluid system status. The process data is logged into the software log files for the operator to monitor the process.

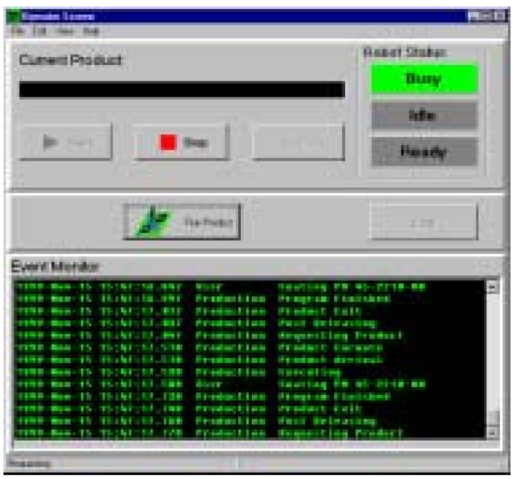

Figure 6. Sample Screen from Selective Coating System

An operator or manufacturing engineer needs an interface to the system that is user friendly and provides useful information about the process. Application-specific, Windows®-based software (Figure 6) designed for conformal coating provides this when general-purpose software usually does not. General-purpose systems involve complicated CNC type codes, which may or may not interface with process controls and provide useful information. The advantage of application-specific software for selective conformal coating is that it allows the engineer to program where the coating should be dispensed, rather than the dispenser's trajectory. Easy-to-use, high-level, dispensing-specific instructions insulate the programmer from the complexities of the underlying hardware and machine language, reducing both training and programming time. The software has integrated instructions to perform and log process control functions. The logged data can be transferred to spreadsheet or other Statistical Process Control (SPC) software for additional process monitoring. Warnings are displayed that are specific to the conformal coating process.

Figure 7. In-Line Board Inverter

Process control components, such as board handling and dispensing monitoring, will improve the system performance and reduce the production defects. Automated product handling reduces the chance for operator error and improves throughput. Every time an operator handles a PCB there is a risk of contamination, dropping the board, or disturbing the uncured coating. Also, static sensitive boards are at risk from Electrostatic Discharge (ESD). Conveyors move boards into and out of a workcell without operator intervention. Many PCBs require coating on both sides, so the board must be flipped. Automated board inverters and flippers (Figure 7) remove the risk associated with operator board handling. With automated handling, boards can pass through the conformal coating process safely and reliably.

As discussed in previous sections, changes in viscosity, caused by temperature, fluid mixture, and time, will change the flow through the dispenser nozzle. Fan Width Control (FWC) for film coaters and Flow Monitoring for other dispensers allow for corrections to be made so the dispensing process is more consistent. Fan Width Control (Figure 8), which resides in the software, automatically measures the fan width with a light beam and adjusts the pressure to maintain the same fan width. Monitoring the dispensed pattern width alerts the operator of potential problems and ensures that the same coating pattern is dispensed every time, thereby improving product quality. The integrated software allows for several procedures to be used. A quick check or measure routine is used in normal production while boards are transported. If the fan width is out of range, a control routine is used to adjust the fan width to the desired width.

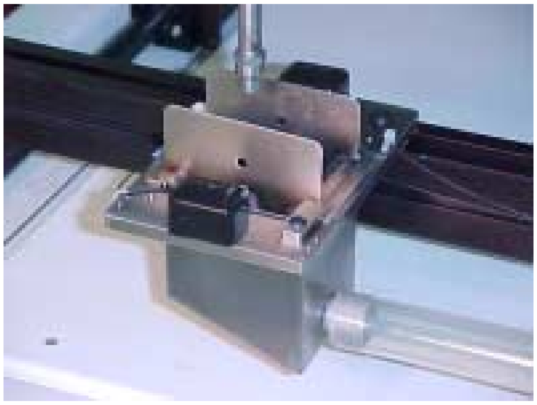

Figure 8. Fan Width Control

Flow Monitoring uses a flowmeter in the fluid line, integrated with the software, to measure the amount of material dispensed onto the product. The flowmeter produces pulses proportional to the volume of flow, which are read by the system computer. The pulses or counts are totaled for the particular board, each count representing a discrete volume of flow. The counts can be tracked for all of the products and upper and lower limits set for the coating process. For example, if a board or pallet requires 2 grams of material and the flowmeter produces one count for 0.038 grams (fluid density=0.9g/cc), the nominal or target counts for that board is 52. (This will be discussed further in the case studies and applications section). Not all flowmeters are created equal. Table 2 shows a relative comparison between different types. Accuracy is one important factor, but robustness and maintainability are also important. For conformal coating applications there are two types that are typically used: nutating piston and gear. The nutating piston flowmeter is very accurate, but it is not tolerant to air purge and if damaged it must be sent to the factory for repair. A properly selected gear flowmeter is as accurate. Regarding robustness and field repair, most gear flowmeters are tolerant to light air purge to flush solvent and coating and can be disassembled in the field.

With any system there are certain guidelines to be considered when selecting the dispensing monitoring system. It is important to know the operating envelope for the control system. The FWC is used for film coaters with a crosscut nozzle. As mentioned previously, this is for coatings in the 10-150 cp range. The Flow Monitoring system can be used for any fluid or dispenser. In conformal coating production the resolution of the flowmeters available is typically 0.04 cc per count. If you are trying to monitor a process that only puts down 0.1 cc of material, the resulting 2-3 counts per board is not sufficient to do any SPC or to sufficiently monitor the process. In this situation the flow is monitored over a series of boards to increase the total counts.

Table 2. Flowmeter Type Comparison

Parameter	Nutating Piston Flowmeter	Gear Flowmeter
Flow Rate Range	4-200 cc/min (1)	4-200 cc/min (1)
Resolution	0.037 cc/count (1,2)	0.042 cc/count (1,2)
Accuracy (1 cc dispensed)	3.6%	4.1%
Accuracy (2 cc dispensed)	1.9%	2.1%
Robustness	Fair	Good
Maintainability	Poor	Good

Note 1: cc=cubic centimeter
Note 2: Resolution based on conformal coating application.

Monitoring the fluid system manually can be tedious and introduce a strong possibility of error. Fluid level sensing and automated material changeover systems significantly reduce the chance of running out of material. Monitoring the fluid level manually can be tedious for the operator and there is a risk of introducing error into the process. If the fluid level is not monitored, the fluid could run out and many uncoated boards could pass through the line before the problem is detected. Most fluid reservoirs are opaque, so operators cannot easily tell when they are empty. Continually opening the reservoir to check the fluid level is not a good idea, because moisture and contamination can enter the fluid system. Adding fluid level sensors and low fluid alarms to the system alert the operator to refill fluid reservoirs before they are empty.

Changing from an empty to full reservoir, if not automated, can be overlooked and takes time away from valuable production time for maintenance. The automated material changeover system allows the fluid system to automatically switch quickly from an empty reservoir to a full reservoir. A typical system has two reservoirs and monitors the weight of each. Assume the conformal coating fluid is currently being pumped from Reservoir A. As the level dips below the low limit, a warning light on the light tower is enabled, indicating the reservoir is nearly empty. As the weight of Reservoir A drops below a low limit, the system releases the pressure in Reservoir A, switches the flow path to Reservoir B, and pressurizes Reservoir B. The fluid in Reservoir A can then be replaced at any time while pumping from Reservoir B. When Reservoir B empties, this process reverses automatically. Some systems use conformal coating materials stored and pumped from bags or bladders that are placed in reservoirs. The closed bags prevent fluid contamination and further reduce the changeover time. The material changeover system eliminates downtime when the reservoir needs to be refilled and reduces the chance of boards passing through the workcell uncoated.

Process Control Case Studies and Applications

The practical application of conformal coating process control is best seen through examples of fan width control and flow monitoring. Fan width control will be used for one example. Two cases, one palletized array of small boards and one large board, will be used as examples for flow monitoring.

In Case 1 a production line is started in the morning and the fan width of a film coater is set. As the shift progresses the temperature in the plant increases from 18 C to 24 C (65 to 75 F). The sample control chart in Figure 9 compares the fan width uncompensated and the fan width under control. For this example the uncontrolled dispenser's fan width increases 17 percent from the initial 12 mm (0.47 inches) width to 14 mm (0.55"), whereas the controlled fan width stays within a controlled range of ±2.5 percent. As the width approaches an upper limit the fan width control system brings the width closer to the target value of 12 mm.

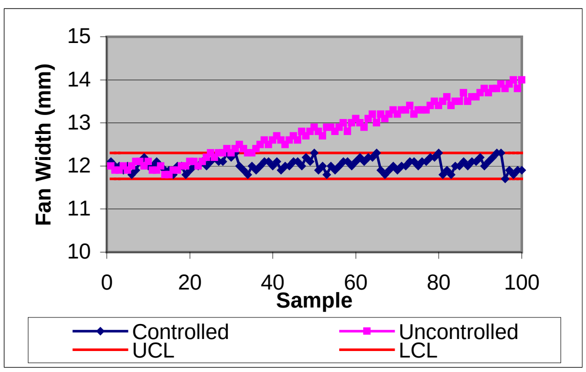

Figure 9. Control Chart for Case 1

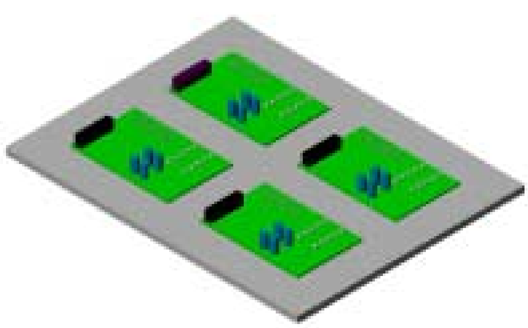

Figure 10. Palletized Boards for Case 2

In Case 2 there are four boards in a pallet and the coating material is an organic fluid with 30 percent solvent. Each board is 5.1cm (2 inches) wide and 7.6 cm (3 inches) long (Figure 10). The average coating thickness (wet) is 0.076 mm (0.003 inches) in an effective coating area of 3.8 x 6.4 cm (1.5 x 2.5 inches). The total coating volume per pallet is 0.737 cc (0.045 in^3). The flowmeter produces K-factor of 23.8 counts/cc for the coating material used in this process. Therefore, the average counts are 17.5 per pallet. In this process the specification is 0.076 mm (0.003 inches) ±0.0127mm (0.0005 in) for the average coating thickness. The upper (USL) and lower (LSL) specification limits are 0.089 and 0.064 mm (0.0035 and 0.0025 in), respectively. This translates to flow counts for the USL and LSL of 20.5 and 14.5 respectively. Since fractions of counts cannot be measured realistically, readings of 20 and 15 are in range and 21 and 14 are out of the range. The process has an allowable tolerance of ±17%, which is within the resolution and accuracy of the meter. The counts per each pallet are logged into a file and can be transferred to a control chart in external software for process tracking (Figure 11). As the process gradually reached the upper limit the operator compensated for the change to bring the process close to the target value.

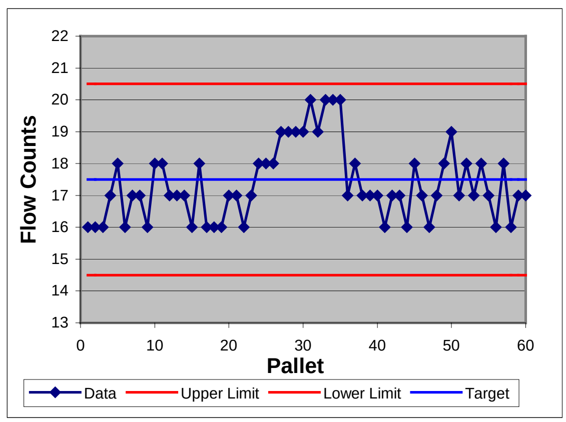

Figure 11. Control Chart for Case 2

In Case 3 a larger board and the coating material is silicone (100 percent solids). The board is 18 x 20 cm (8x7 in). The average coating thickness is 0.15 mm (0.006 in) in an effective coating area of 15.2 x 15.2 cm (6 x 6 in). The total coating volume is 3.5 cc. Using the same K-factor as in Case 2, the total counts are 84. In this process the specification is 0.015 mm (0.006 inches) ±0.025mm (0.001 in) for the average or target coating thickness. The upper (USL) and lower (LSL) specification limits are 0.18 and 0.13 mm (0.007 and 0.005 in) respectively. This translates to flow counts for the USL and LSL of 98 and 70 respectively. As in Case 2 the process has an allowable tolerance of ±17%. Similarly, the counts per board can be logged into a file and loaded into a control chart for process tracking.

Summary

Selective conformal coating systems improve the process by taking the human factor out of the equation. Improved dispensing technology and application-specific software produce a more repeatable coating from board to board. The automated system allows for easy integration of process controls, which monitor and control the fluid dispensing. By integrating process control into the selective coating system the product defects are reduced and the manufacturing engineer has the tools to track the process.

References

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