Developing SPC Methods for use with AOI Equipment in a Contract Manufacturing Environment

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Abstract
In-line inspection equipment has become common place in the PCB assembly industry. This equipment is intended to both eliminate defects at an early stage of production and to be used as a process control tool to prevent these defects from occurring in the first place. In practice the full benefits of the applied Statistical Process Control (SPC) methods have typically not been realized even though many of today's Automated Optical Inspection (AOI) systems come equipped with built-in SPC tools. In this paper we will discuss how a contract manufacturer and an AOI vendor have worked together to develop SPC tools and methods for solder paste printing using a 3D solder paste inspection system.

Introduction
No surface mount assembly process attains 100% first pass yield. Yield losses result in scrap, rework, or both which cost businesses in terms of materials, equipment and labor. Many electronics assemblers who have purchased AOI equipment have achieved cost benefits using the tools to detect defects early in the manufacturing process. These assemblers are eager to discover how the same tools could be used for process control to actually prevent defects by improving the process. However process control cannot be installed in the way you install a printer. While AOI equipment must provide useful data analysis tools, successful implementation of process control requires a strong management commitment to the endeavor and a careful consideration of which tools are the most appropriate for a particular manufacturing environment.

A contract manufacturer needs to assemble a large variety of products and technologies. Product turnover and sometimes operator turnover can be high. Often a single SMT line must be capable of building several types of products and several lines must be capable of building the same product to accommodate fluctuations in customer demand cycles. At the Celestica facility, build sizes range from 50 to 500 pieces and most product types have topside joint counts from 15,000 to 30,000.

GSI Lumonics and Celestica Toronto have been working together to establish statistical process control tools that are useful for any paste inspection process as well as specific features that are critical to the contract manufacturer. Developments in the AOI software tools have enabled process improvement successes at the contract manufacturer in the last year. This paper discusses the implications of the contract manufacturing environment to the selection and implementation of process control tools and describes some of the achieved benefits.

The Paste Inspection Equipment Used
The GSI Lumonics Model 8100 is an in-line, automated inspection and process control system that utilizes proprietary 3-D laser technology and advanced image-processing capability. 3-D technology enables the system to directly measure solder paste volume and has the added benefit of being insensitive to color and contrast changes. The 8100 system is designed to inspect solder paste deposits and component placement on PCB assemblies at line rates. This AOI equipment is capable of making the following process measurements for each solder paste deposit on a board:

- between pads (area of coverage
- area centroid and displacement of solder deposit
- volume of solder deposit
- average height of solder deposit
- peak height of solder deposit
- bridging attribute only)

The specification limits for determining the pass/fail condition of the measurements are determined and set by the user. The process measurement data produced can also be used to drive real-time SPC charts, which allows the user to monitor the solder paste screening process live.

3D Data Acquisition

The 3-D data of the board surface is created using a triangulation method that utilizes a solid-state scanning and detection system in conjunction with signal processing electronics to collect accurate, high-speed height data. A laser diode is used to project a spot of light onto the board surface. The position of the reflected light is focused onto a position sensitive photodetector that is offset from the beam. The height of the board surface is determined by the sensed position of the reflected laser light on the photodetector. Analog electronics then convert each detected spot into a digital word coded with a discrete height value. The laser beam is raster scanned to collect a series of height points that form a line. The scanner is moved by a precision positioning system to collect successive lines of data. The process is continued until the entire board surface is scanned. Each 3D height pixel can be coded to one of 256 possible height values. The resolution of the standard scanner is approximately .001 inch in X and Y, and .00023 inch in Z.

The scanner is equipped with two detectors that are designed to eliminate blind spots where the projected spot cannot be seen by one of the detectors. The high-speed data acquisition rate of the scanner allows the system to collect a high density 3-D image rather than sample cross sections. This results in an accurate representation of the size and shape of each feature on the board. Figure 1 shows a diagram of how the 3-D laser scanner works.

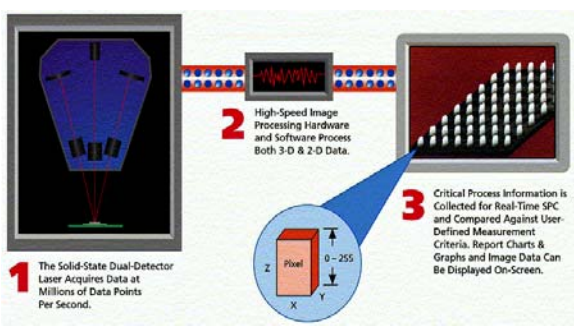

Figure 1 – 3D Scanner Theory of Operation

Automatic Paste Inspection Methodologies

Most published end-of-line defect Pareto charts indicate that the solder process accounts for the majority of end-of-line defects, typically 40-60%[1,2]. Figure 2 shows a typical end-of-line defect Pareto. Further detail concerning where these defects originate and the products they are associated with are needed to determine the most cost effective inspection strategy for a product. Generally speaking, solder paste inspection can be used for defect detection, process control or a combination of both.

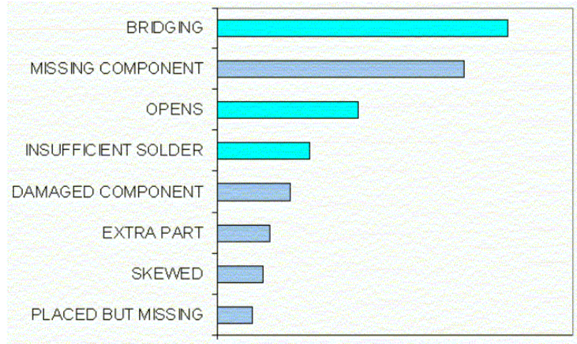

Figure 2 – Typical Defect Pareto

Defect Detection – Defect detection is a reactive measure taken to find bad products that require repair and is accomplished by comparing measurements of a product to user-defined specification limits. Defects can occur randomly and can either be identified in-process or at the end of the line. Defect detection can improve yield when it is implemented in the early stages of the process. Defect detection also can support limited process control by feeding back attribute data so an operator can determine and address the root cause of the defect, preventing further detects.

Process Control – Process control is a preventative measure taken to find abnormal sources of variation in the process and eliminate them. Statistical methods are typically used to detect abnormal process variation. Problems found at this point may not result in a hard failure of the product at the end of the line. SPC methods alone will not fix the process when problems are found. Once abnormal variation has been flagged the responsibility of taking proper action falls on those directly connected with the operation. Both attribute data and variable data fuel SPC methods. Taking an SPC approach requires a strong commitment on behalf of the manufacturer to supply well-trained resources to support this effort.

Challenges **-** The primary challenge of implementing defect detection strategy is deciding where to set the specification limits. Commonly limits are set at or near +/- 50% and they often vary per package type. In theory specification limits should be set at a point where a known defect will occur at the end of the line. The difficulty with solder paste inspection limits is that there is a gray area where a given solder paste deposit may or may not result in a defect depending on other factors such as lead formation, lead coplanarity, or reflow profile. Setting tighter specification limits may catch more of the marginal paste deposits, but this approach is likely to impact production throughput. A better solution is to additionally use process control methods to keep the paste printing process better centered in the first place thus producing few pads that fall into the marginal category while continuing to use defect detection to catch random defects.

Choosing the Right SPC Tools for the Job

There are numerous SPC tools and methods available to the SMT process engineer. Run charts and Pareto charts (histograms) are the two common categories for charts and there are several varieties of each.

Pareto charts are used to plot attributes, or categories of defect types vs. defect frequency. Pareto charts can be used to quickly identify to the most common defect types and locations. The AOI software includes Pareto charts for plotting defect type vs. package type and defect frequency vs. location on the board[3].

A run chart monitors process performance over time both in terms of target value (how centered is the process) and dispersion (how much variation exists in the process). The AOI solder paste inspection software includes an Average run chart (Xbar chart) for tracking the location of variable measurement data and either a Range run chart (R chart) or Standard Deviation run chart (S chart) for tracking the dispersion of variable measurement data[4]. The advantage of the run charts over offline audits (e.g. paste height) for measuring process performance is twofold. First, these charts enable you to capture much more information about print quality because measurement data from a large number of features are grouped onto a single chart. Second, measurement error is diminished significantly by plotting group averages instead of individual measurements.

The inspection equipment supplier needs to develop SPC tools that have the right features to be effective and easy to use by factory personnel. What should the charts look like? How many charts should there be? What options need to be available to the end user to accommodate the range of user groups? With input from Celestica, improvements to the software have been implemented.

One improvement to the charting software concerned the application of appropriate color coding to the user interface. An early version of the run chart software connected data points using a red line regardless of whether the data were in control. Factory personnel were sometimes confused by the presence of this color to represent data in control since it is common in the factory to declare “we’re green” when the process is in control or “we’re red” when the process is out-of-control. This minor modification to the application had a big payoff in the effectiveness of the data presentation.

For the assembler and the types of products produced at the facility it was important to select the right software charting options. In many cases the wrong decisions were made at the start and changes were subsequently implemented. An important decision faced early on was how to select useful and rational subgroups. Celestica aimed to represent a large proportion of the features on every board, and to balance this against the quantity of charts that an operator looks at. The software makes available different options. Subgrouping can be done by device (i.e. reference designator), by template (i.e. package) or by template class (i.e. group several packages together).

In early attempts to use run charts during production builds at the Celestica facility, run charts were set up for different template classes. All templates with similar aperture sizes were grouped together and named according to a technology class, "20 Mil” or “uBGA”. We discovered two problems with this method of subgrouping. First, it added significantly to the setup time for a program (approximately 45 minutes) since we would have to classify devices within subgroups even before selecting any run charts. Second, while the labels on the subgroups were meaningful to process engineers, they were not very meaningful to line operators who for other process steps subdivide boards according to reference designators. We decided to create run charts for those locations that are the most challenging to print and to use reference designators as the subgroup category. This way operators could easily connect the data displayed on screen to the corresponding location on the board.

Another key decision for the contract manufacturer is how to set control limits. There are several options available for setting control limits on the equipment’s run charts. Control limits can be input manually (calculated using data from a similar production run) or they can be automatically calculated.

Again, to keep program setup as simple as possible the automatic limit calculation option was selected. To proceed with this option there are two settings the user must define:

1. Stop Updating Control Limits After ___ cards
2. Start Testing Control Rules After ___ cards.

At the outset the settings were selected to Stop Updating Control Limits After <u>30</u> cards and to Start testing control rules after <u>10</u> cards. However some difficulties were experienced when control limits were recalculated for only the first 30 cards due to intermittent process shifting. To avoid frequently resetting charts, the control limits were set to recalculate after every card. This setting worked well for the early stages of implementation but due to other practical challenges was eventually changed to 100 cards.

Challenges of Applying AOI Equipment and SPC Tools in the Factory

Beyond the challenge of selecting appropriate charting features, practical challenges implementing screening process controls in the factory were faced especially in the early stages. A major challenge of making run charts useful is determining how a user should interact with the data.

Clearly the most important aspect of interacting with data on control charts is determining how to respond to the data. The charts can tell you when your process is out of control, but they don't tell you what to do about it when that happens. This is exactly why SPC cannot simply be installed into a factory. What Celestica has found is that discovering sources of variation and learning how to address them is an ongoing learning process. Furthermore, in the early stages this learning process can be a time consuming effort. SMT throughput was halved for the first several shifts of production implementation, speeding up as they learned how to react appropriately to the data.

One of the ways Celestica has made reacting to the data manageable is to deactivate some control rules. Our intention was to only enable control rules that an operator can intuitively link to the process and respond. As a result, the following two control rules are the only active rules on all Xbar and S charts:

1. 1 point outside control limits
2. 6 consecutive points increasing or decreasing

Due to the automatic and ongoing calculation of control limits in the early stages another way operators needed to interact with the data was to disable certain data points. This activity was necessary since some data points did not reflect the printing process (e.g. bare boards) and would falsely widen the limits and mask true out-of-control conditions. What Celestica found was that operators accepted this initially, paying close attention to spurious data and disabling those points. But it became difficult for operators to continue doing this for an extended period since it is a time consuming and not an obviously meaningful activity. The solution would require a change to the way we set control limits, limiting the number of boards over which control limits are calculated (i.e. 100 boards).

At the outset Celestica expected to take advantage of a feature of the control charts where a user is prompted to enter a comment when an out-of-control condition is detected. One of the practical difficulties we found in using this feature was a problem of timing. At the time that the software prompts for comment, the operator cannot visually verify the location on the board since it is inside the machine. Consequently Celestica disabled the automatic prompting for comment when an out-of-control condition is found and decided instead to add comments only when a known a process change has occurred. Some examples for comment are when a stencil is washed, paste is added or replaced, or a printer setting is changed.

Further organizational challenges were encountered during the early stages of production implementation. For the purpose of initiating SPC with solder printing Celestica sought to dedicate a number of operators on every shift to the pilot study line. This way these operators could be trained prior to the study and would contribute to the learning curve throughout. Because this type of resource structuring is not typical for the contract manufacturing facility, there were instances where new operators needed to be trained throughout the project.

As well, conducting the study when manufacturing lines do not always run at full capacity posed a challenge. These challenges are not identical for every assembler but they will occur in some form and tend to affect the continuity and momentum of the learning process. Planning for them as much as possible up front should impact the clarity of the study results.

Benefits of Using SPC with Paste Inspection

Several assignable causes of variation have been uncovered in the solder paste printing process by implementing SPC with paste inspection. Variation in average paste volume due to differences in the print stroke direction was one of the causes identified in Figure 3. To effectively remove this variation in one instance both squeegee blades were replaced with new ones.

Also, Celestica has seen the impact of a time gap in the printing process. The quality of the first few boards printed after a break can be poor (e.g. low average volume, high standard deviation) until the paste is worked again (Figure 4). Operators now use the run charts to help identify when the paste has been adequately worked.

A third assignable cause that has been identified relates to using a new (different) stencil (Figure 5). The impact of process changes like this are now apparent in an instant instead of only coming as a result of time consuming offline data analysis.

On top of the specific lessons already learned, a significant benefit of using SPC with paste inspection is that it has enabled constant learning about the printing process. Operator confidence in the tool is bolstered because the AOI with SPC does much more for them than inspect product. It has become a tool that they can rely on to manage and maintain the solder paste printing process.

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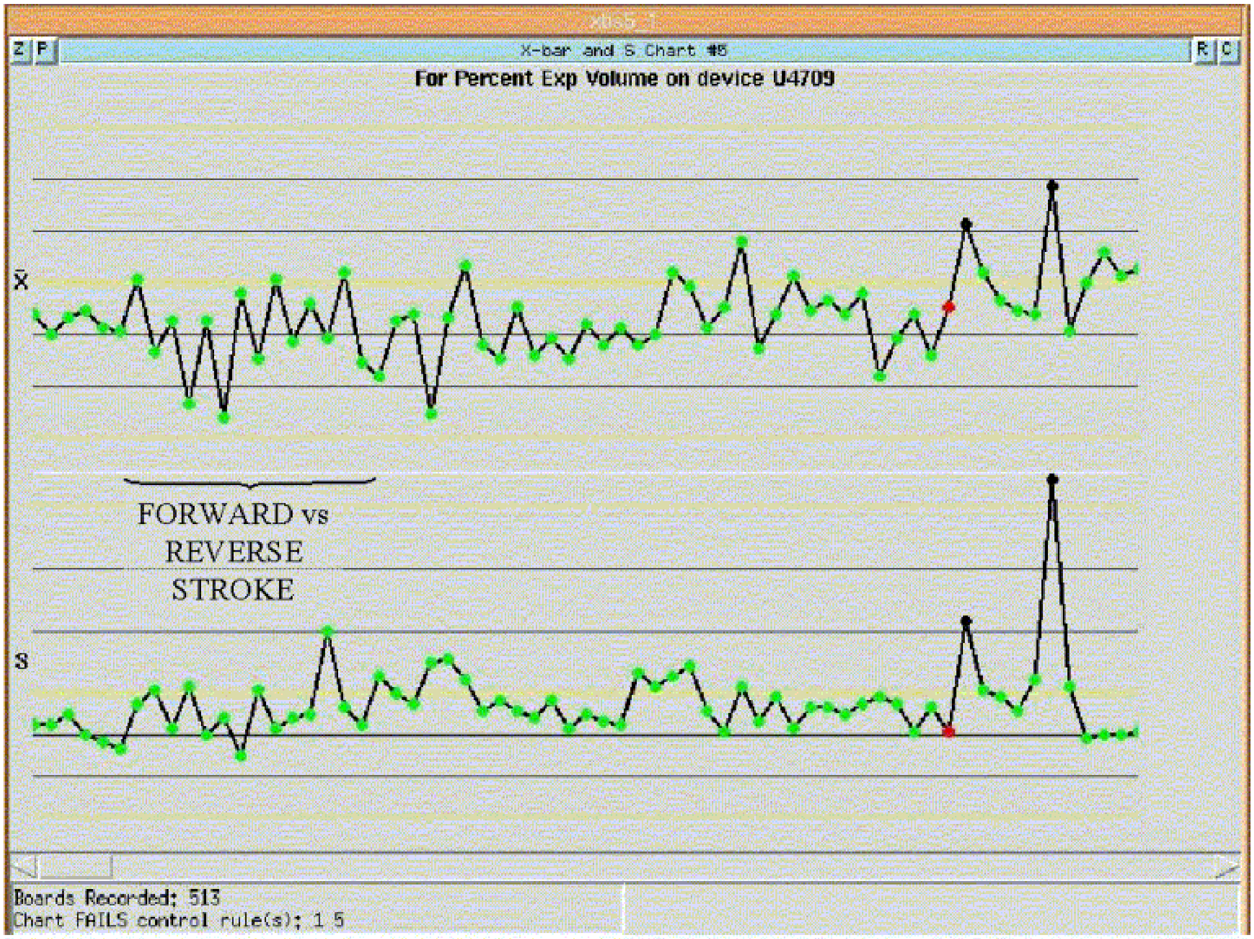

Figure 3 – Alternating Print Stroke Direction Causes the Paste Volume to Oscillate Around the Process Grand Average

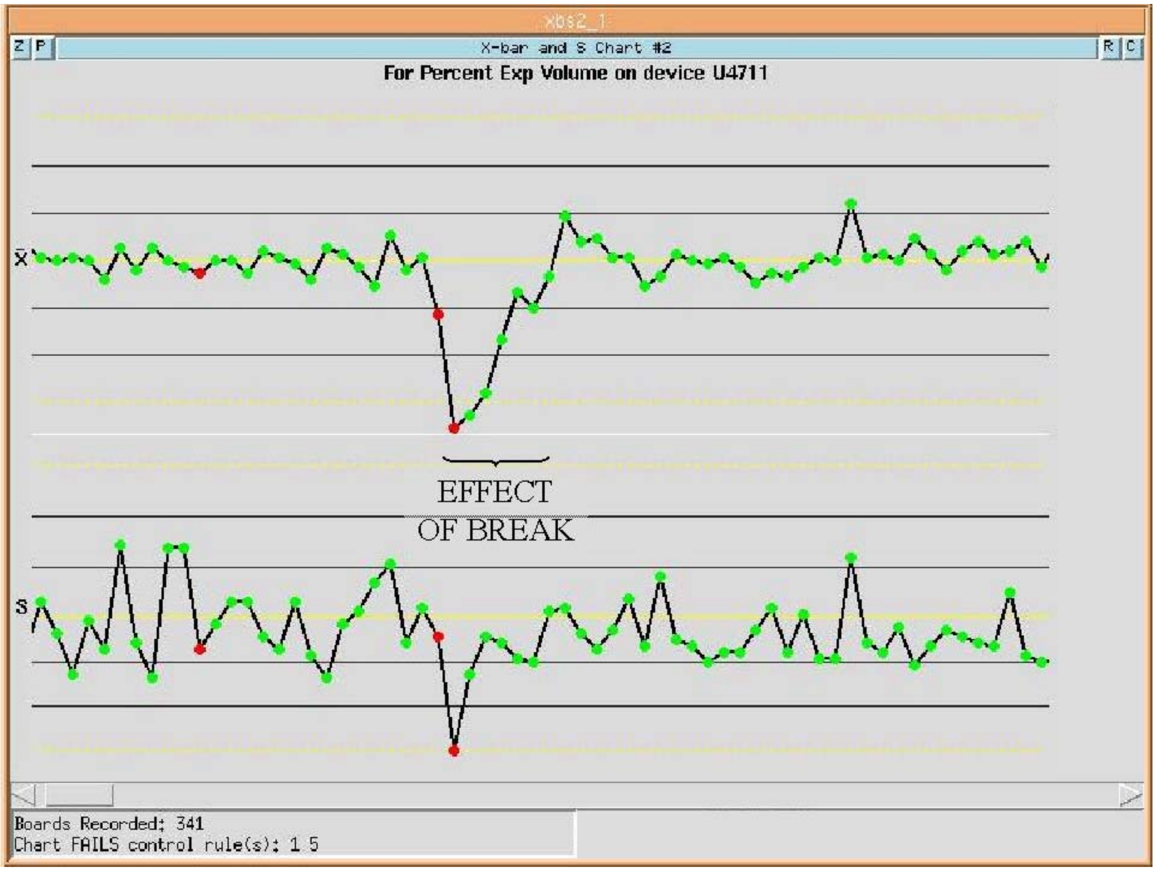

Figure 4 – The paste Volume Mean Dramatically Shifts Temporarily after an Operator Break

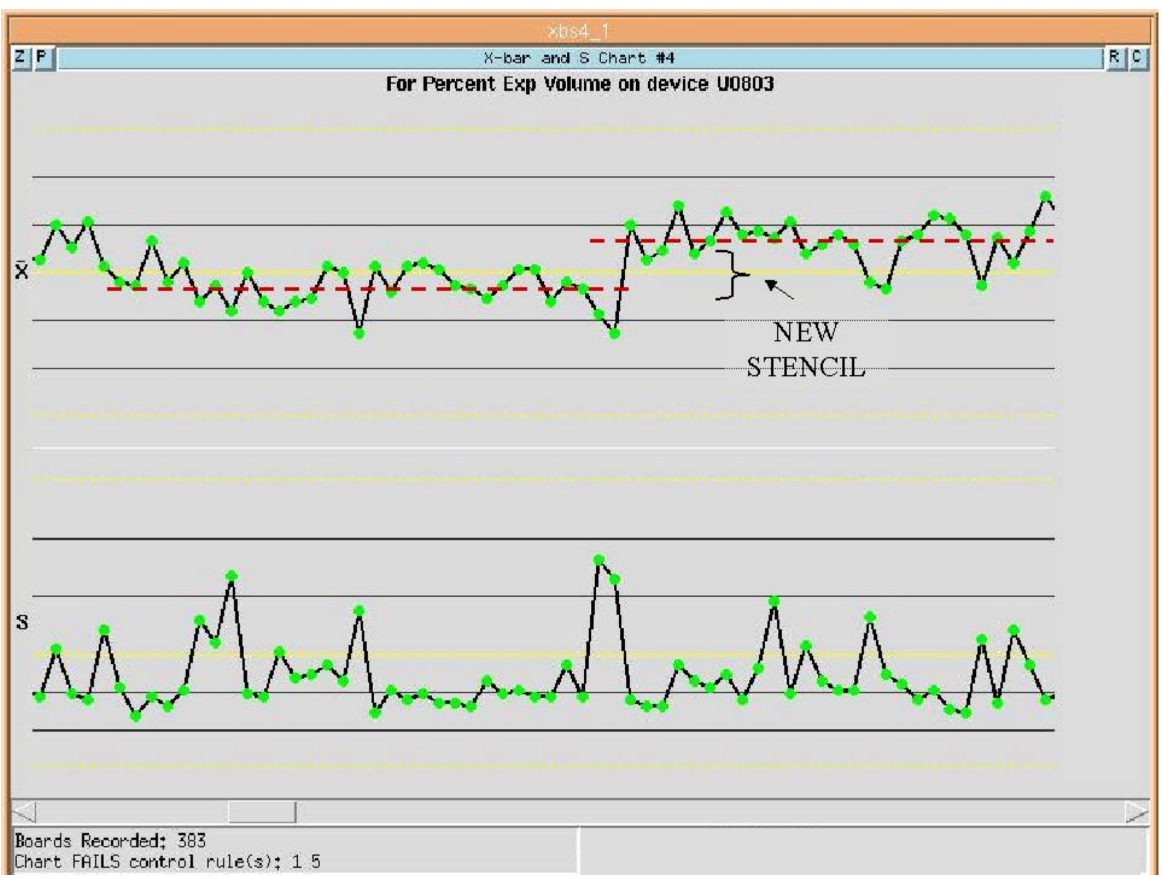

Figure 5 – The Paste Volume Mean Shifts Permanently after a Stencil Change