SIMPLE, EFFECTIVE PROCESS CONTROL IN WAVE SOLDERING

Chrys Shea
Siemens Information and Communication Networks, Inc.

Introduction

Many expensive defects produced by the wave soldering process are caused by process parameters operating outside their normal windows, and can be prevented by the application of process control. Although wave soldering has not historically been considered a well-controlled process, the changes the process has seen over the past decade make it a prime candidate for effective control methods. These methods are not complex, but relatively simple and inexpensive to implement and maintain.

This paper outlines the harmful effects of out-of-control process parameters and describes methods of measuring and tracking them to keep them in control. It addresses all critical variables of wave soldering: flux deposition, preheat application, conveyor speed, solder temperature and solder contact time.

Critical Variables

The three basic elements of forming a high quality solder joint are **flux**, **heat** and **solder**. Without any one of the three, a reliable solder joint cannot be efficiently produced. Therefore, critical variables in the wave soldering process must include flux specific gravity and deposition rate, preheat and solder temperature, and solder dwell time.

What happens if any of the critical variables are outside their process parameter window?

The criticality of a flux's specific gravity depends on the type of flux under consideration. The performance of high solids fluxes is less sensitive to fluctuations in specific gravity than low-solids formulations. The reliability of assemblies processed with high solids fluxes is also less dependent on density fluctuations because harmful residues are removed in the cleaning process that is normally associated with high-solids fluxing.

The performance of low-solids, or no-clean, fluxes is very sensitive to fluctuations in density. A low-solids flux that is too dilute can cause poor wetting or open solder joints; flux that is too dense can leave harmful residues on assemblies that jeopardize their reliability.

Flux deposition is critical to good soldering. Too little flux can cause open joints and webbing; too much flux can cause solder balls or (again) leave harmful residues that are not removed in modern no-clean operations.

Proper heating of the substrate and components is important not only to solder joint quality, but to overall assembly reliability. Too much preheat can contribute to topside surface mount component reflow. Not enough preheat can cause a multitude of problems. Poor solderability can result if the components being soldered are not hot enough to wet in the limited amount of time they are exposed to the wave. Underactivating fluxes can cause poor solderability and a rosin "sludge" to build up on the surface of the solder pot. Extreme thermal excursions at the point of contact with the solder wave can shock delicate components, causing permanent damage that may not manifest itself at in-circuit or functional test.

Finally, the solder itself is a critical variable. Contact with molten solder is the largest thermal excursion in the wave soldering process. Reliability of the assembly is maintained through specific cycles of solder contact for which the components were designed. Quality of the assembly depends on proper heat transfer, solder wetting and peel off from the wave.

A multitude of process defects and product reliability issues can arise if any of the critical variables are running outside their process windows. But they cannot be controlled without first being accurately and repeatably measured.

Measuring critical variables

Flux

Flux specific gravity can be measured and controlled in many ways. High solids fluxes are less sensitive to minor fluctuations in specific gravity and tolerate open systems, such as wave or foam fluxing, well. Most wave soldering systems utilizing open fluxers are equipped with closed-loop feedback systems such as density floats or PAAR meters that continually add flux or thinner to maintain the specific gravity between identified specification limits. If the measuring devices are calibrated and periodically checked with a hygrometer, they will provide good information.

Low solids, or no-clean fluxes, however, are much more sensitive to specific gravity variations caused by the evaporative nature of their carriers (alcohol or water). If used in an open system, these fluxes can not be adequately maintained by automated systems, but instead require frequent titrations to measure and adjust their density. A typical measurement interval for no-clean chemistry in an open system is one to two hours. To overcome the time consuming, operator dependent nature of these fluxes, they are typically stored in sealed systems and dispensed as needed by a time/pressure method.
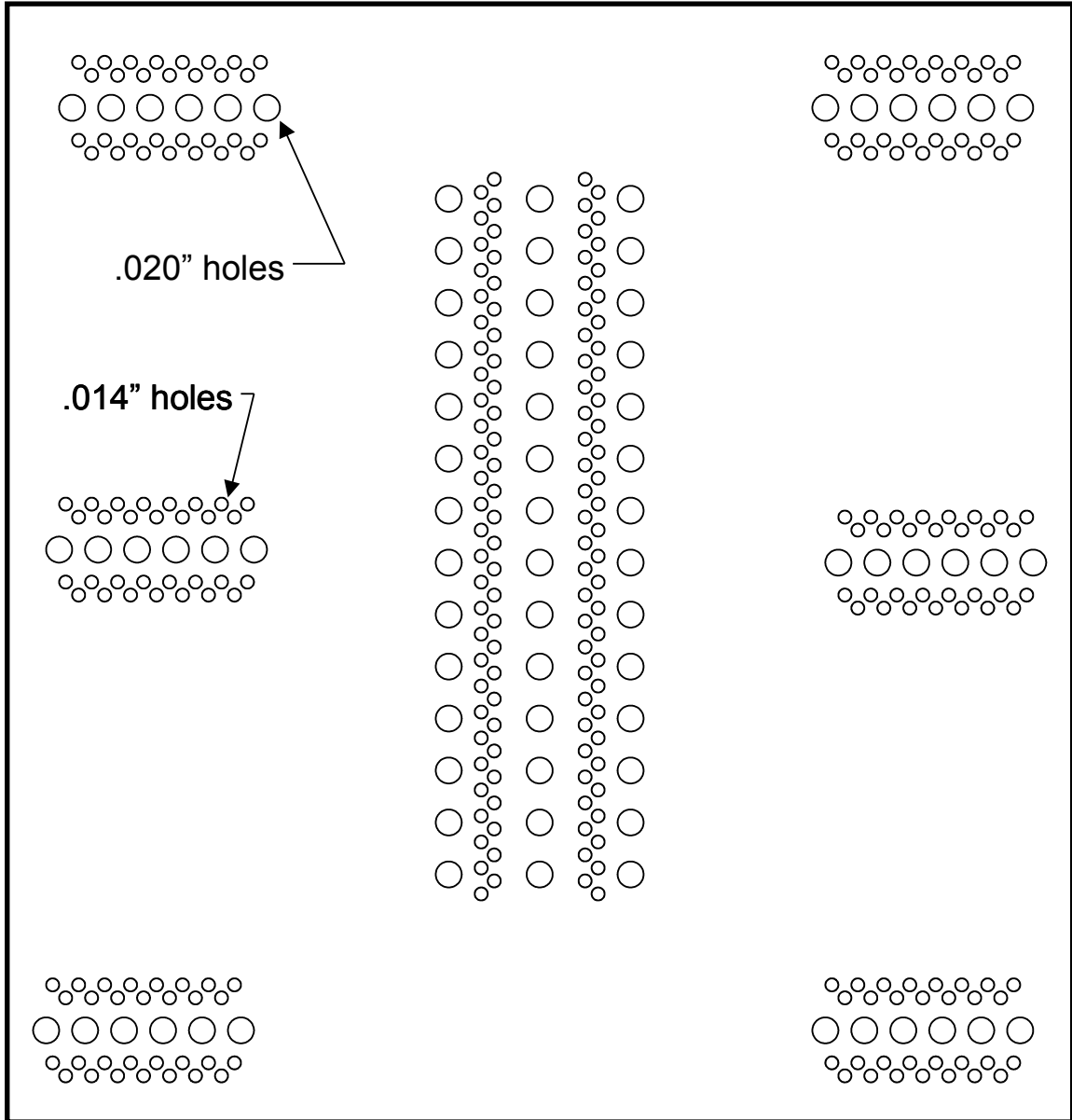
Alcohol-based fluxes must be overpressured with nitrogen to prevent alcohol evaporation within the storage tank, whereas low-VOC, water-based fluxes can be overpressured with air.

The amount of flux applied to a circuit board and the uniformity of deposition is absolutely essential to good soldering. An easy and effective method of measuring deposition is by weight. A non-porous plate (typically aluminum or stainless steel) is weighed. Flux is applied, and the plate is weighed again, before the carrier evaporates. The weight differential is multiplied by the solids content of the flux and divided by the area of the plate. The resulting deposition, usually quoted in micrograms per square inch, can be compared to the manufacturer's recommendations and tracked using common SPC techniques. If more evaporative alcohol-based fluxes are used, corrugated board may be substituted for the non-porous plate, because the absorption of the cardboard retards the evaporation.

Uniformity of deposition is also easy to measure.   While performing weight tests, visual inspection of the flux deposit is a primary indicator of uniformity. A more precise indicator of a fluxer's uniformity uses chemically sensitive paper sandwiched between two plates. The upper plate is used only to support the paper; the bottom plate has hole patterns drilled in it as shown in figure 1. As the fixture passes over the fluxer, flux penetrates the holes and changes the color of the paper. By removing the bottom plate, the paper can be inspected across the process width for uniform deposition. Thermal fax paper is a widely available and economical paper to use with alcohol-based fluxes. It will change into various shades of gray, depending on how much alcohol it has absorbed, which makes it an excellent tool for diagnosing overlap or non-uniformity of spray fluxing systems.

Figure 1
Diagram of Fax Paper Test Fixture

.020" holes

.014" holes

Preheat
The proper amount of preheat for any circuit board is defined by the individual board's density, and should be determined by standard thermal profiling

methods. The amount of heat a machine's preheater provides at a particular setting should be monitored to assure repeatability of the thermal profile. Convection preheaters can be monitored by a calibrated thermocouple. Infrared preheaters are more subject to variation than their convection counterparts, but their output can also be easily measured by many of the process control devices on the market today. These devices consist of a thermocouple embedded in an epoxy/glass laminate substrate, and are usually features of wave solder process control devices. The output of the device is the temperature of the substrate. It should be stressed, however, that *it is an indicator of the thermal output of the preheaters, not the temperature of the preheaters themselves.* This data can be compared over repeated sampling intervals using common SPC techniques to indicate repeatability of the preheating system.

Solder

Solder temperature can be quickly and accurately monitored with a calibrated thermocouple. Although solder pots are on closed-loop feedback control with permanently mounted thermocouples, periodic checks are recommended for two reasons. First, periodic checks aid in maintaining calibration of the thermocouple. Second and more importantly, dross buildup around a thermocouple insulates it, effectively slowing the feedback loop and causing the temperatures to swing higher and lower than necessary.

Solder contact time and uniformity can be measured by a variety of techniques, the simplest of which is a temperature-resistant glass plate running on conveyor fingers. Best results are achieved when the plate is fluxed and preheated like a circuit board to promote good wetting. The conveyor can be stopped to position the glass over the wave, where the contact length of the wave is measured at both sides of the process width. Uniformity of contact can be determined by calculating the difference in contact lengths from one side of the process width to the other side. Contact time can be calculated by dividing the contact length by the conveyor speed used in a particular recipe. Figures 2 and 3 depict uniform and non-uniform solder contact.

Conveyor speed is critical to repeatable solder contact times. If the wave solder machine is not equipped with a closed-loop control system on the conveyor drive, a hand held tachometer can be used to measure conveyor speed. Accurate readings require about 10 inches of travel, so the best setup uses a rigid plate on the conveyor and a positive stop for the tachometer. The positive stop prevents variations introduced by hand movements, and can simply be a part of the machine that the tachometer can be held against to keep it still. Readings should be taken at loaded and unloaded conditions to assess the variations in motor speed.

Figure 2
Uniform Wave Contact Against a Glass Plate

Figure 3
Non-Uniform Wave Contact Against a Glass Plate

Many process control devices are marketed to characterize wave parameters. These devices automate the solder contact measuring processes previously described. Their primary outputs are wave contact and solder temperature. Some devices also report conveyor speed, contact length, and immersion depth of the wave. A 1994 study of these devices by the author showed the Malcolm Dip Tester to be the most repeatable and reproducible of these devices. The Dip Tester uses a set of two contacts which, when submerged in the wave, connect a timer. Some of the outputs of this device are

the contact time in both turbulent and laminar waves, reported individually in tenths of a second. The tester is run through the wave in a fixture with two apertures, one on each side of the process width. The two readings are then compared to indicate parallelism. The inherent disadvantage of requiring two passes over the wave are offset by the high degree of accuracy of the device and its ease of use.

Measurement Frequency

How often a process control measurement should be taken depends on the process and equipment under consideration. A key factor in determining measurement frequency is whether or not the output in question is directly controlled by the machine, or affected by external variables that are not under the machine's control.

Modern wave solder machinery is typically equipped with relatively sophisticated closed-loop feedback control systems, which monitor performance and adjust output at predetermined time intervals. Subsystems like preheaters and conveyor drives are constantly monitored by the machine itself, and are usually not affected by external variables for which the machine cannot compensate. These systems do not require frequent measurements, but rather periodic checks.

Other variables, however, are affected by external sources for which the machine may not be able to compensate. Examples of these variables are wave contact and flux deposition. Wave contact can be affected by many factors, including the conveyor speed, the amount of dross constricting the flow ducts, the amount of solder in the solder pot, or the position of the pump's impeller relative to the flow duct. Although the solder machine can continually monitor and adjust the speed of the pump, it can neither control nor compensate for internal dross buildup. Likewise, flux deposition can be affected by cleanliness of the flux nozzle, the draw of the exhaust system, or fluctuations in shop air pressure. Although a flux delivery system can accurately meter flow rates or pressures, it cannot always keep its spray head clean or its exhaust flow constant. Dependent variables such as wave contact and flux deposition should be monitored more frequently than independent variables.

Age, calibration, and maintenance history also factor into measurement frequency. Inherently stable subsystems, such as solder pot heaters, do not require close measurement intervals.   If particular subsystems of a machine have historically been stable, their measurement periods can be extended longer than subsystems which have exhibited instability. The best way to determine stability is by collecting baseline data and analyzing its variation.

Baseline Data

Baseline data serves several purposes in process control. Baseline capability studies provide indicators of stable (high Cpk) or unstable (low Cpk) subsystems. Baseline data also provides a benchmark for comparison with future readings to note performance variations. Finally, baseline data can provide an excellent troubleshooting tool. When a particular subsystem is not performing to expectations, data can be compared to help isolate the cause of variation.

Table 1 depicts baseline data for an Electrovert Econopak Plus®. The data was taken when the machine was new, prior to any production service. The variables were monitored directly from the machine's computer using Electrosoft® software for remote monitoring.

<center>**Table 1**
Baseline Data for Electrovert Econopak Plus</center>

Variable	Setpoint & Limits	Cpk
Solder Temperature	500° F ± 10°	2.41
Preheat Zone 1	330° F ± 20°	6.03
Preheat Zone 2	320° F ± 20°	5.32
Preheat Zone 3	330° F ± 20°	2.50
Conveyor Speed	6 ft/min ± 0.1 ft/min	1.75
Lambda Pump Speed	1100 rpm ± 10 rpm	2.35
Chip Pump Speed	1600 rpm ± 10 rpm	2.01

<center>**Cpk**</center>

What is Cpk?
Cpk, the process capability index, relates the allowable tolerance of a process to its natural variation. It is a statistical measurement based on the ratio between a process' output and its specification limits. Cpk is calculated as the lesser of:

$$\frac{\bar{X}\text{-LSL}}{3\sigma}$$

<center>or</center>

$$\frac{\text{USL-}\bar{X}}{3\sigma}$$

where: $\overline{X}$ represents the average of the process output
                σ represents the standard deviation of the process output
                LSL is the process' lower specification limit
                USL is the process' upper specification limit

What does Cpk mean?

If a process' output were plotted on a histogram and compared to the specification limits of the process, Cpk would describe the shape of the bell curve (tall and thin or short and wide) and how well it was centered within the specification limits. Table 2 below enumerates the number of times a process' output will occur outside of its specification limits for each benchmark of the capability index.

Table 2
Cpk and statistical defect rates

Cpk	Out-of-specification occurrences
.33	3 in every ten
.67	5 in every hundred
1.0	3 in every thousand
1.33	7 in every hundred thousand
1.67	6 in every million
2.0	2 in every billion

SPC Implementation

Many machine variables can be easily measured and monitored. Engineers should use caution when determining which factors to measure and monitor. Monitoring too many variables decreases production efficiency. Monitoring the wrong variables may provide a false sense of security about a process that is drifting out of control.

Several factors should be considered when determining which variables to monitor under SPC. Designed experiments can indicate which variables have the greatest impact on process output. Baseline data can indicate the stability of the subsystem controlling these variables. Variables that have a large impact on process output or have demonstrated instability should be closely monitored under SPC. Dependent variables that cannot be fully controlled by the machine itself are SPC candidates.

The results of SPC should be reviewed periodically. Defects should be correlated to SPC charts. If no correlation is present, the variables under control

should be reviewed. If variables show consistently high Cpk's, the control limits and sampling frequency should be reviewed. If low Cpk's can be attributed to cyclic behavior (such as steadily increasing wave contact between solder pot cleanouts), the cyclic behavior can be tracked to keep the process in control and raise the Cpk.

A Process Control Model

No two machines or processes function in identical manners; therefore, a model of process control is just a model. The user should determine critical variables and measurement techniques. The model introduced here is based on a 1997 Electrovert Econopak Plus®, equipped with an Opti-Flux® reciprocating head ultrasonic spray fluxer, three convection preheaters, nitrogen inerted rotary chip and laminar waves, and a hot nitrogen knife.

Baseline data was collected during acceptance testing at the factory. Critical variables were determined through prior experimentation and user experience on the equipment under consideration. Critical variables included:

- Flux deposition rate
- Preheat temperatures
- Conveyor speed
- Solder temperature
- Solder pump speed

These variables are retested on a quarterly basis. Flux deposition rate and solder wave contact and parallelism are tested twice daily. They are tested at the beginning of each shift, employing the philosophy that the operator should not begin producing circuit assemblies unless s/he knows that the process is under control. Table 3 details the variables, specification limits, and Cpk's that are monitored on daily basis.

Table 3
Capability Data for Wave Solder Machine

Variable	Setpoint & Limits	Cpk
Lambda Wave Contact	1.3 sec ± 0.2 sec	1.62
Chip Wave Contact	0.3 sec ± 0.2 sec	1.68
Flux Deposition	500 μg/in² ± 100 μg/in²	2.42

The Benefits of Process Control

The obvious goal of controlling manufacturing processes is minimizing defects. Preventing defects is less expensive that fixing them. But defect mitigation is only one of many benefits of process control. Other benefits include:

- Troubleshooting process or equipment problems becomes easier when current performance trends can be compared to historical data, minimizing costly downtime.
- Keeping processes in control helps to guarantee product reliability.
- Performing experiments involving process or product changes in controlled environments provide for accurate analysis.
- Operators who are involved with controlling processes understand them better.

Monitoring processes may take a small amount of time away from production, but the returns of process control go directly to a company's bottom line. In the price-competitive electronics industry, higher profits can be realized by lowering operating costs. Reduced defect rates, reduced rework, more machine uptime, fewer warranty repairs, and accurate gauges of process modifications all provide a direct path for lowering operating costs and increasing profitability.

Acknowledgements