As originally published in the IPC APEX EXPO Conference Proceedings.

Position Accuracy Machines for Selective Soldering Fine Pitch Components

Gerjan Diepstraten
Vitronics Soltec B.V.
Oosterhout, Netherlands

Abstract
The drive towards fine pitch technology also affects the soldering processes. Selective soldering is a reliable soldering process for THT (through hole) connectors and offers a wide process window for designers. THT connectors can be soldered on the top and bottom side of boards, board in board, PCBs to metal shields or housing out of plastic or aluminum are today's state of the art.

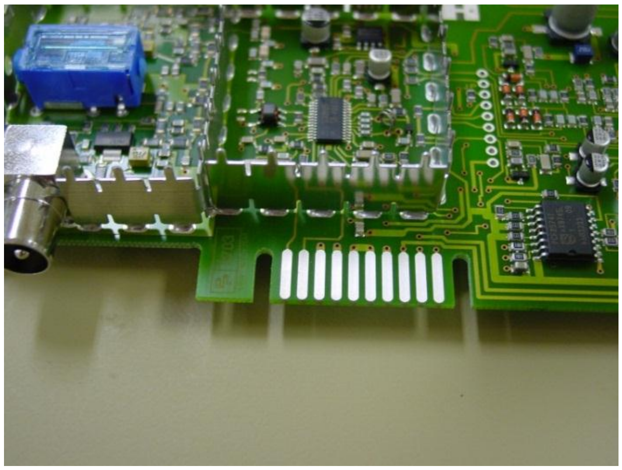

Figure 1: Example of selective soldering metal shielding

The materials that are used to make the solder connections require higher temperatures. Due to the introduction of lead-free alloys, the boards need more heat to get the barrels filled with solder. This not only affects the properties of the flux and components, but the operation temperatures of solder machines become higher. A nitrogen tunnel wave solder machine requires a temperature control in the tunnel to prevent overheating. Advanced systems are available that insert cold nitrogen. The closed tunnel wave soldering process has a wide process window and is not sensitive to small changes in environmental conditions. The same counts for wave solder machines that have nitrogen blanket systems over the wave. Improved preheaters will bring sufficient heat in the assembly and exhaust systems are adequate enough to maintain required process conditions. The nitrogen will improve the soldering and minimize dross amounts at these elevated solder temperatures.

Selective soldering is a different process. Compared to wave soldering there are additional process parameters that are affected by the higher temperatures. Solder joints have to be made close to SMD pads or components. An off-set of 0.5 mm may result in solder skips or re-melting SMD components. The higher temperature may cause warpage of the board, which also affects the position accuracy of the solder nozzle. All materials will expand at higher temperatures, but not all expansion coefficients of the materials used are equal. This not only introduces stress, but also may create off-sets.

Introduction

First the impact of temperature will be discussed for the separate process steps and for machine tooling. In the experimental part measurements are done to verify the accuracy that can be achieved using today's selective soldering machines. Dedicated tooling is designed to achieve special requirements with respect to component position accuracy.

Flux unit:

A selective soldering process has three process steps: fluxing, preheating and soldering. During the first step, the fluxing of the solder side of the assembly, the board and machine parts have an ambient temperature. A high frequency drop-jet device is able to apply very fine droplets. The device is mounted on a robot that is moving in a x,y direction to shoot these fine droplets on those spots where the printed circuit will meet the liquid solder. The position of the flux is critical. Not only should the flux be on the soldering area to clean the board and support the wetting, but there should not be flux anywhere else on the board. It can be critical if non-activated flux is mixed with solder paste flux residues close to the soldering spot. Any non-activated flux on the assembly may cause electro-migration in the field when it is exposed to humidity and a bias. Flux that is not applied correctly may affect reliability of the product, not during production, but during the life time of the product.

Flux amount and position should be controlled to avoid field issues. The robot in the machine should move the drop-jet to the right spot. These locations are imported from the CAD-files or by teaching the cold print by a camera.

Preheat unit:
After the flux is applied the board is transferred to the preheating unit. This can either be an IR lamp device or a forced convection heater. The board is heated to a topside temperature of 120 ºC. A typical FR4 board has a CTE (Coefficient of Thermal Expansion) of 14 ppm/ºC in x-direction and 17 ppm/ºC in y-direction at temperatures from ambient to the Tg (glass transmission temperature) of the board.

The heating will extend the board length:

A FR4-print is heated to 120 ºC (ΔT = 100 ºC). The length of the board is 250.00 mm. After preheating the board will have a length of 250.35 mm. Not only should the expansion of the print be considered, but also the warpage. Due to the heat and mass of components the warpage might give problems in the z-position. This deviation in the z-axis can be measured with laser sensors. The offset data is used to modify the robot position towards the solder nozzle to have a consistent contact time/immersion depth all over the print. If not compensated, warpage may give open joints (no contact or contact with solder too short) or bridging (contact time too long). An alternative to compensate warpage is to have dedicated tooling vacuum or mechanical holders installed in the gripper that keep the board flat.

Robot gripper:
After preheating the board is picked up by the robot. The robot will move the print to the soldering station where the board has to be positioned towards the solder. First the position of the board in the gripper has to be defined. There are different ways to define the print location:

- Fiducial camera – A camera can recognize fiducials on the print and calculate the off-set of the fiducials to a reference point.
- Mechanical fix – The majority of the printed circuit boards has tooling holes for positioning the print in fixtures and machines to process the board. Pins in the gripper will lock the board in the defined position.

The machine software knows where the robot is and once the print is locked or defined by the fiducial camera, the position of the print is defined in the software.

Dip soldering station:
The robot will move the print to the solder unit. There are two soldering options: dragging over a small nozzle or dipping on a nozzle plate. First dipping will be discussed.

For high volume assemblies the dip soldering on a nozzle plate that is dedicated for each print design is the most efficient method for a short cycle time. In one single dip all solder connections are made. It is a challenge to dip a preheated printed circuit board onto a nozzle plate that is installed in liquid solder of 280 – 320 ºC. The nozzle plate is made with the Gerber/CAD data of the assembly. The temperature difference and expansion of the stainless steel is compensated. The CAD data has the dimensions defined at ambient temperature, but in the selective dip process the robot (aluminum) may have a temperature of 50 ºC, the print (FR4 material) 120 ºC and the nozzle plate (stainless steel) 320 ºC. Different temperatures, CTE’s and materials should result in a robust process where joints are soldered up to 1 mm from surrounded SMD, metallized pads or other components.

In order to match the hot nozzle plate with the preheated printed circuit board the following equation can be used:
$L_{Nozzle\ (Ta)} / L_{PCB\ (Ta)} = (1 + Ec_{PCB} * (Tp - Ta)) / (1 + Ec_{Nozzle} * (Ts - Ta))$

The factor $L_{Nozzle\ (Ta)}$ / $L_{PCB\ (Ta)}$ expresses the multiplication factor for the nozzle plate dimensions at ambient temperature related to the PCB dimensions at ambient temperature, so that both will fit at soldering conditions.

L_{PCB} = PCB length [mm]
L_{Nozzle} = Nozzle plate length [mm]
Ta = Ambient temperature [ºC]
Tp = Preheat temperature [ºC]
Ts = Solder temperature [ºC]
Ec_{PCB} = Thermal Expansion Coefficient of the PCB [ppm/ºC]
Ec_{Nozzle} = Thermal Expansion Coefficient of the nozzle plate [ppm/ºC]

All the programming needed to solder the board can be done off-line on a separate computer. However, teaching of the machine points can only be done in a machine that has achieved its operation temperature. The robot has to learn where the machine points are. Machine points are the reference of a part in the process, like teach camera, solder pot, pick up, and fluxer position. To compensate, temperature differences and expansion differences of the different parts fiducials can be installed in the machine. With a fiducial camera mounted on the gripper it is possible to make corrections if required. The camera on the gripper measures the offset of the solder pot and the software will guide the print in the correct position. Dip soldering is an application that is common used in high volume lines where cycle time is critical so the camera should respond fast to minimize time loss.

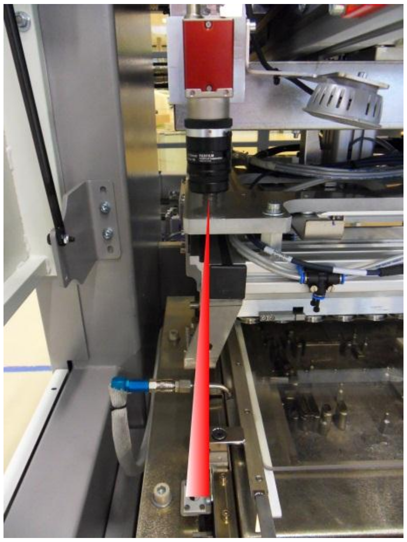

Figure 2: The camera mounted on the gripper verifies the position of the solder pot by checking the location of the fiducials.

Another method that is used for most assemblies is to have a position pin on the gripper that slides into a position hole on the nozzle plate. Thus the position of the print toward the nozzle plate is mechanically secured. Also, this point has to be learned with a machine at operation temperatures otherwise, due to difference in expansion, the robot might have an off-set of 1 mm or even more.

On the nozzle plate there are spacers installed with a defined height. In this way the z-position of the print is always guaranteed and board is kept in a flat position.

Drag soldering station:

The more flexible soldering method is to have a small nozzle and drag the assembly over the wave. This single point soldering is a robust method, but it is time consuming and creates longer cycle times. There are four methods for drag soldering. The first selection is the nozzle material. This can be wettable or non-wettable. Second, one can solder horizontal or under an angle.

For a non-wettable nozzle the solder flow direction is defined and the board or the nozzle should have a U-rotation option to drag the print in the right direction over the wave. For a wettable nozzle the solder overflows in all directions which make it possible to drag the print from all directions.

Nozzles have different shapes and even may have a different height. Therefore the machine should have a dedicated machine point for each nozzle. After changing a nozzle this machine point may have been changed in x, y-position or even in height (z-position). A general rule is that after maintenance or removing parts, machine points have to be verified to avoid small offsets. The nozzle has been taught and the position of the print in the robot gripper is mechanically secured or defined by fiducials, so all required information is there for the system to drag the board properly over the small nozzle without touching the surrounded SMD components. The board warpage should be compensated by to robot z-position to avoid that the board is immersed too deep in the solder.

Experiment:
The next experiments are done to verify the accuracy of the robots used to transport the print to the proper position. These measurements are also part of the quality program that is run for every new machine before production starts. For many automotive lines this capability analyses are repeated before an audit or after the machine has been moved. Each machine has at least two robots. The drop-jet nozzle of the fluxer is installed on a x,y robot. This moves the drop-jet to spray at those spots that require flux. A very sensitive liquid flow measurement guarantees a controlled flux amount per connector. The low flux flow can be measured using a device that contains a heating element that registers every temperature change which is directly related to the flow rate of the flux. A fork laser sensor can be used to define if the sprayed flux is going in the right direction, perpendicular to the print. For a given flux type, machine settings and solder mask the software will define the spread of the flux on the board ensuring there is no excess flux on the assembly.

Flux Robot Accuracy Test: To define machine capability (accuracy of the flux robot) laser sensors were installed to measure the distance of the robot to a pre-defined point. Repeatability is required without influence by environmental noise, like temperature and humidity changes.

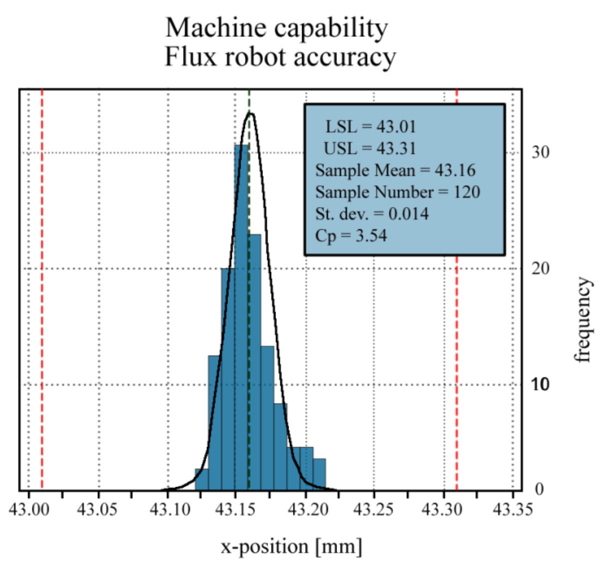

Figure 3: showing the normal distributed placement accuracy of the fluxer robot in the x-direction.

For the flux robot, an accuracy of ± 0.15 mm is defined in the specification. As shown in the graph the robot is capable and has a standard deviation of only 0.014 mm. The robot moved 120 times to this position over a time period of two hours. No drift was visible in the raw data. The robot was even more accurate in the y-direction where the standard deviation was only 0.007 mm.

Gripper Robot Accuracy Test:
The robot gripper that picks up the board after preheating and moves the printed circuit board exactly above the nozzles in the

solder pot has to be more accurate than the flux robot. The specification of this unit is defined ± 0.10 mm. This is more accurate than systems that move a solder pot underneath the printed circuit board. Using an identical measurement device as in the previous test the x, y and z-direction of the gripper robot are tested for consistency. Despite the higher specified accuracy the x, and y-direction positioning of the gripper robot proved to be consistent. For both directions the standard deviation is approximately 0.008 mm resulting in Cp values of approximately 4.

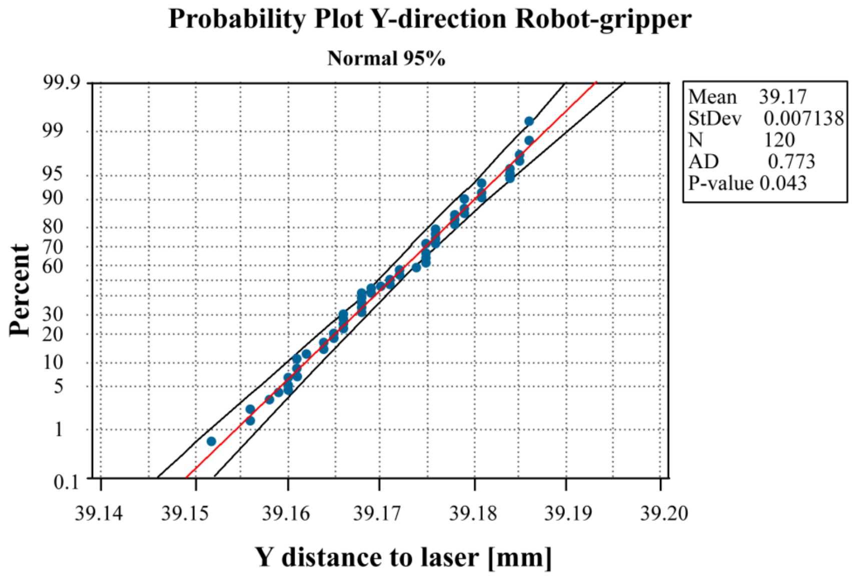

Figure 4: Probability plot of the y-direction robot gripper.
Consistency of placement, measured toward laser sensor.

When the pins on the board are dipped into the solder the height (z-direction) of the robot gripper should be placed at the correct height. The board may warp due to the higher temperatures. To make sure that the board is not touching the nozzle rim, which would result in solder webbing/oxides on the solder mask, the nozzle plate has stand-off pins to support and level the board. The robot gripper itself is also accurate in z-direction. The standard deviation is equal to x and y-direction, 0.008 mm.

Select wave nozzle

Multi wave nozzle plates have stand-off pins which provide a mechanical means to fix the z-position. The small select wave nozzle has no mechanical tooling to secure the height which makes this soldering more challenging. Three parameters are critical and all have variation: board flatness (warpage), z-position accuracy of the robot gripper, and the stability of the wave height.

How stable is a small wave?

In order to address the wave height stability of a small nozzle a special test with a camera measuring the wave height was designed.

For a given design of nozzle there are three factors that define the wave height and its stability:

1. Solder alloy
2. Solder temperature
3. Pump speed

For the experiment, a 5 mm (inside diameter) wettable nozzle was used. The solder was lead-free SACX and the solder temperature varied from 280 – 320 ºC.

Table 1: showing the average wave height at different pump settings.
The number of samples is 120 for each setting.

Wave height [mm]		Solder temperature [°C]				
		280	**290**	**300**	**310**	**320**
Pump speed [rpm]	**455**	2.10	2.17	1.98	2.02	1.99
	460	2.41	2.45	2.41	2.38	2.43
	465	2.60	2.64	2.61	2.56	2.59
	470	2.75	2.80	2.76	2.71	2.74
	475	2.86	2.88	2.85	2.80	2.83
	480	2.97	3.03	2.96	2.90	2.90
	485	3.04	3.02	3.00	2.96	2.98
	490	3.14	3.20	3.10	3.07	3.05
	495	3.21	3.29	3.17	3.10	3.20
	500	3.31	3.36	3.29	3.18	3.17

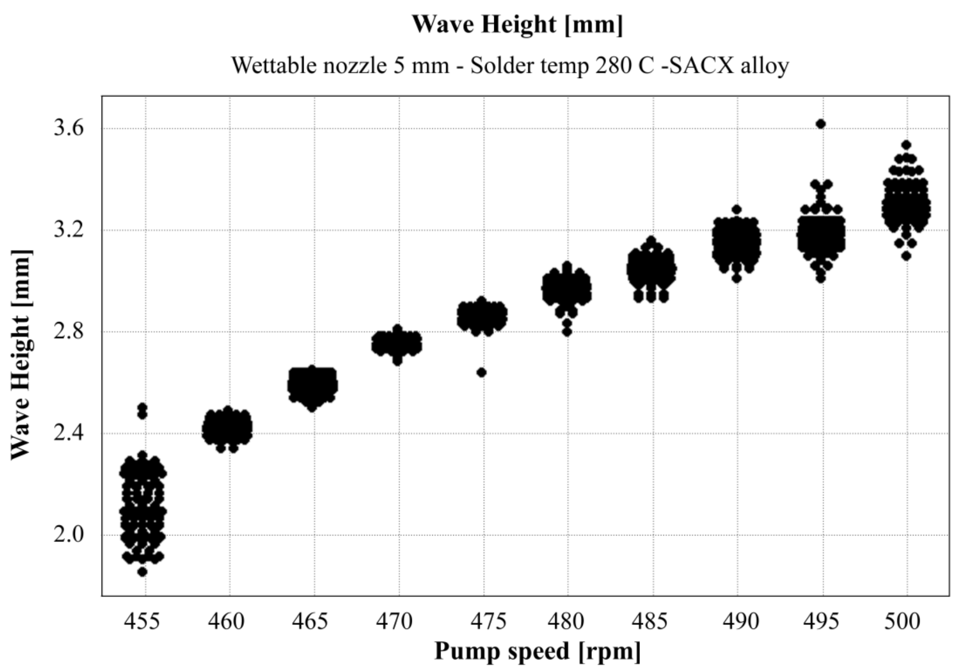

Figure 5: showing the variation in wave height as a function of the pump speed.

The wave height of the select wave can be controlled by the pump speed. As shown in the figure above, there is a small process window. The height can only be changed with a few rpm's, otherwise it becomes more unstable. In this example the wave height is most stable between 2.4 and 2.9 mm (460 – 475 rpm).

Special tooling and component accuracy:

In a robot gripper, dedicated tooling can be installed for increased accuracy or for special requirements. Examples of these tools are:

- Topside heaters to reduce temperature drop and keep the board at temperature;
- Cooling devices to avoid overheating of components;
- Vacuum or other devices to keep the board flat and avoid warpage;
- Tooling to prevent components from moving or lifting due to the heat of the solder; and
- Tooling to keep the component in place and achieve accurate placement (up to flatness of -0 to + 0.1 mm).

Conclusions:

Selective soldering is a robust soldering process when the process parameters are addressed and under control. In the different process steps we identified critical parameters:

Flux process - In this first process there are no elevated temperatures and accuracy is established by:

1. Accurate x, and y position of the robot;
2. Flux flow measurement; and
3. Verification of the flux flow direction.

Preheat process - No special requirements for board handling or placement accuracy. The temperature of the print is measured with a pyrometer to guarantee flux activation and prevent overheating.

Dip soldering process - Several requirements need to be fulfilled to have a consistent dip process.

1. Position of the PCB in the gripper has to be defined:
   a. mechanical fix, or
   b. fiducial recognition
2. Position of the nozzle plate must be defined:
   a. machine point verification with fiducials, or
   b. mechanical fix of PCB/gripper with nozzle plate
3. Z-direction is guaranteed by stand-off pins on the nozzle plate.

Drag soldering over select wave - The requirements for a consistent drag process are:

1. Position of the PCB in the gripper has to be defined:
   a. mechanical fix, or
   b. fiducial recognition
2. Machine point of the nozzle should be verified:
   a. fiducial x, and y position
   b. z-height verification with a sensor
3. Z-position of the PCB is critical during soldering. Special attention is needed to make sure that there is no excessive warpage. Special tooling in the gripper or warpage compensation (measured with laser) by software are methods to compensate for a lack of flatness.

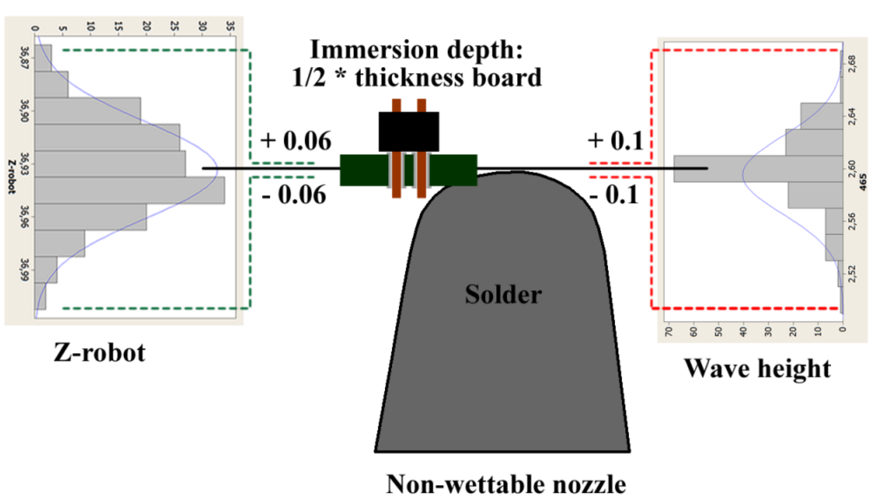

Figure 6: this schema shows the variation of wave height and robot in z-direction. Most critical for this process is the flatness of the board.

Experience and machine capability data show that despite the temperature changes and board warpage, THT connectors can be soldered in a very accurate way. The knowledge of the process and small, but very efficient, tooling devices help improve accuracy. Special designed nozzles have non-wettable screens mounted on top to avoid bridging. This option requires a place accuracy of 0.10 mm. The robot showed to have a consistent placement accuracy that can meet the tough placement requirements with the help of mechanical fixtures or fiducials.

References:

1. http://www.pcb007.com/pages/zone.cgi?a=71427 (PCB 101: Coefficient of Thermal Expansion), September 2010, Bob Tarzwell, DMR Ltd.
2. "Tools to increase the process window of a selective soldering process.", EPP Europe, November 2013, Gerjan Diepstraten, Vitronics Soltec.
3. "Selective soldering in an optimized nitrogen atmosphere.", OnBoard magazine, April 2013, Gerjan Diepstraten, Vitronics Soltec.