Effects of PCB thickness on adjustable fountain wave soldering

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Abstract. This study investigates the effects of printed circuit board (PCB) thickness on adjustable fountain and conventional wave soldering. The pin-through-hole (PTH) vertical fill is examined with three PCBs of different thicknesses (i.e., 1.6, 3.1, and 6.0 mm) soldered through adjustable fountain and conventional wave soldering at conveyor angles of 0° and 6°. The vertical fill of each PCB is the focus. The PTH solder profile is inspected with a non-destructive X-ray computed tomography scanning machine. The percentages of the PTH vertical fill of both soldering processes are also estimated and compared. The aspect ratio of the PCB is also investigated. Experimental results reveal that adjustable fountain wave soldering yields better vertical fill than conventional wave soldering. The vertical fill level of adjustable fountain wave soldering is 100%, 90%, and 50% for the 1.6, 3.1, and 6.0 mm PCB thickness, respectively. FLUENT simulation is conducted for the vertical fill of the solder profile. Simulation and experimental results show that the PTH solder profiles of the two soldering processes are almost identical. The effect of PCB thickness on PTH voiding is also discussed.

Keywords. Pin through hole (PTH); adjustable fountain wave soldering; wave soldering; printed circuit board (PCB); vertical fill; simulation.

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1. Introduction

Wave soldering is widely utilized to solder pin-through-hole (PTH) components onto printed circuit boards (PCB) in the electronics assembly industry. Typical PTH components, such as micro-controllers, resistors, capacitors, IC sockets, and pin connectors, are fixed on PCBs through wave soldering. Prior to wave soldering, the bottom surface of PCBs is sprayed with flux to remove any oxide layers on the PCB and pin. The PCB is then pre-heated to a desired temperature to activate the flux and prevent thermal shock. The PCB is placed over a solder pot. The waveform molten solder and the bottom surface of the PCB are placed into contact with each other, and the molten solder fills the PCB hole through a capillary action. The filled PCB hole solidifies and forms a solder joint at the cooling zone. An insufficient vertical fill, usually less than 75%, is considered defective according to IPC-A-610D (IPC 2005).

Many studies have been conducted on wave soldering and its various aspects, including its material and mechanical characteristics (Kuo *et al* 2013), PTH defects (Suganuma *et al* 2000), low silver alloy (Wang *et al* 2013), the intelligence system of the process control (Pietraszek *et al* 2014; Liukkonen *et al* 2009), and process optimization (Liukkonen *et al* 2011; Huang *et al* 2012). Most of these studies were conducted through experiments. The type of solder material used significantly affects the reliability of a PTH solder joint. The use of Sn–0.7Cu–0.05Ni as a solder material can improve the tensile strength of PTH (Kuo *et al* 2013). However, PTH lift-off (Suganuma *et al* 2000) occurs at the top of the PCB when Sn–Bi alloy is utilized. The presence of anti-oxidation elements in a low-silver lead-free solder material enhances oxidation resistance but causes poor wettability (Wang *et al* 2013). Defects in the solder joints are always a problem for engineers in the electronics assembly industry. Thus, an intelligence system (Pietraszek *et al* 2014; Liukkonen *et al* 2009) has been developed and employed to identify defects and determine their dominant process parameters during wave soldering. Process optimization (Liukkonen *et al* 2011; Huang *et al* 2012; Wang *et al* 2011) (i.e., self-organizing maps and multivariate analysis) has also been employed to control the quality and reliability of PTH solder joints during wave soldering.

Tiny PTH and limited equipment have created difficulties in visualizing the real-time PTH filling process. Simulation modeling technique helps engineers understand the process of PTH filling. Simulation tools, such as OpenFOAM (Inagaki *et al* 2013) and FLUENT (Abdul Aziz *et al* 2013), have been employed in various studies on the wave soldering process. Such studies focused on the vertical filling of the PCB hole. The flow behavior of the molten solder was simulated and visualized with a simulation tool in these studies. For example, Inagaki *et al* (2013) investigated the dynamic movement of the molten solder through a simple 2D model. Abdul Aziz *et al* (2013, 2014c) employed CFD modeling and FLUENT to simulate the capillary flow in wave soldering. The effects of pin offset (Abdul Aziz *et al* 2013) and shape (Abdul Aziz *et al* 2014c) on the filling mechanism were investigated numerically through a 3D model. The simulation analysis was extended through thermal coupling method Abdul Aziz *et al* 2014a, b). The thermal-induced displacement, stress, and temperature of the pin were also discussed based on the simulation results. Vertical fill and the solder profile are influenced by PTH diameter and offset angle. Aside from the process parameters, the optimized PCB hole and PTH design are also important factors that influence the vertical fill during wave soldering.

2. Problem statement

The vertical fill of a PCB hole is always a concern in the electronics assembly process. A vertical fill of less than 75% is considered defective in most applications. However, a vertical fill of 50% is acceptable under specific conditions when PTH is connected to thermal or conductor layers that function as thermal heat sinks (IPC 2005). An increase in PCB thickness may affect the percentage of vertical fill during wave soldering. Conventional wave soldering machines (e.g., single or dual soldering pot) are typically utilized in the industry. Although wave soldering technology is well established, the vertical fill of the PCB hole still requires proper process control. Several conditions, such as an unstable waveform, insufficient waveform height, improper dwell time, and preheating temperature, may affect the performance of the vertical fill. The adjustable fountain wave soldering machine was developed to enhance the wave soldering process. The fountain waveform is generated from the pressure nozzle of the machine. In the current study, PCBs with various thicknesses are soldered with adjustable fountain (0° conveyor angle) and conventional (6° conveyor angle) wave soldering machines.

3. Experimental setup

In the electronics assembly industry, wave soldering has numerous functions, such as component hybrid circuit assembly, component lead tinning, and wire tinning. However, it is mainly utilized to solder of circuit board assemblies. PTH components, such as the pin, resistor, and light emitting diode, are inserted into the PCB hole and carried by the conveyor to the soldering zone. The soldering process begins when a mechanical bond is formed between PTH and the PCBs passing through the molten solder. This study investigated the effect of PCB thickness on the vertical fill of the PCB hole. Three PCBs with different thicknesses (1.6, 3.1, and 6.0 mm) and 100 samples of PTH were utilized as shown in figure 1. The PCB dimensions were $120\text{ mm} \times 80\text{ mm} \times 1.6\text{ mm}$ (figure 2(a)). Two types of PTH shape (i.e., circle and square) were assembled onto the PCBs as shown in figure 2(b).

Wave soldering experiments were performed with a conventional wave soldering machine (figure 3) and the proposed adjustable fountain wave soldering machine to investigate the vertical

Figure 1. PCBs at different thicknesses ($1.6\text{ mm} < t < 6.0\text{ mm}$) used for adjustable fountain and conventional wave soldering process.

Figure 2. Sample of PCB used for adjustable fountain and conventional wave soldering process. (a) Plain PCB; (b) PCB with PTH components.

Figure 3. Schematic diagram of the conventional wave-soldering machine.

Figure 4. Laminar and chip wave of the conventional wave-soldering machine.

fill of the molten solder in the PCB hole. A Sn63Pb37 solder was utilized, and the soldering zone of both machines was set to 250°C. The PCB and PTH components were assembled at a conveyor angle inclination of 6° in four process zones (i.e., fluxing, preheating, soldering, and

Figure 5. Schematic diagram of the adjustable fountain wave-soldering machine.

Figure 6. Schematic illustration of adjustable pressure nozzles for the adjustable fountain wave-soldering machine.

cooling zones). In the fluxing zone, the bottom of the PCB was sprayed with flux using an open-nozzle sprayer with air pressure. The PCB was then subjected to an open-type preheating system in the preheating zone. The sensor of the propeller (at the soldering zone) was activated after the PCB passed the preheating zone. The laminar and chip waves of the molten solder generated by the propeller (figure 4) soldered the PCB and PTH components. Finally, the PCB was transferred to the cooling zone for cooling and solidification.

In the newly developed fountain wave soldering machine (figure 5), the PCB was inclined at a conveyor angle of 0° . An ultrasonic atomizing flux spraying system was introduced in the fluxing zone to allow for denser and more uniform fluxing than that in the open nozzle of conventional fluxing spray technique. The PCBs were then conveyed to the closed-type preheating system of the preheating zone. Unlike the open-type preheating system in the conventional wave soldering machine, this system controls the heat distribution to the PCB and reduces the heat that is usually lost to the environment. The PCB was then conveyed to the closed soldering zone. The new adjustable fountain wave soldering machine is equipped with adjustable pressure nozzles (figure 6), which were used to induce high energy from the molten solder to the PCB by adjusting the air pressure. The molten solder rises and fills the space between the PCB hole and PTH at a certain vertical filling level. Figure 7 shows the fountain wave generated from the pressure nozzles. The filled PCB holes were solidified at the cooling zone.

The vertical filling of solder joints was examined with the non-destructive X-ray CT scanning machine of the Institute of Microengineering and Nanoelectronics, University Kebangsaan Malaysia, Malaysia. This machine was utilized because of its capacity to produce tomography images of the specific soldered vertical fill without any damage. Figure 8 shows the X-ray CT scan and sample of the PCB with PTH after wave soldering. Three-dimensional images of the height of the vertical fill (from the bottom to the top of PTH) were obtained and void formation in the solder joint was determined through digital geometry processing. The solder profiles of the adjustable fountain wave soldering machine at vertical fills of 50%, 75%, and 100% were compared with those in the simulation results.

Figure 7. Generated fountain wave solder from the pressure nozzles.

Figure 8. X-Ray CT scanning machine and specimen of PCB with PTHs.

4. Governing equations

In the wave soldering process, after the molten solder interacted with the bottom surface of the PCB, the capillary effect drives the molten solder to fill the space. The motion of capillary flow in the PCB hole is described by the governing equations. The capillary flow was modeled by using the commercial FVM simulation software FLUENT (Yapici *et al* 2005). The molten solder and air were considered as two different phases. The 3D fluid motions were assumed to be incompressible and were described by the conservation of mass, momentum, and energy as follows:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad (1)$$

where u , v , and w are the velocity in the x -, y -, and z -axis, respectively.

Momentum equation (Ramdan *et al* 2012):

x -direction

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \eta \left[\frac{\partial}{\partial x} \left(\frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\partial u}{\partial z} \right) \right] + \rho g_x \quad (2)$$

y -direction

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \eta \left[\frac{\partial}{\partial x} \left(\frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\partial v}{\partial z} \right) \right] + \rho g_y \quad (3)$$

z -direction

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \eta \left[\frac{\partial}{\partial x} \left(\frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\partial w}{\partial z} \right) \right] + \rho g_z. \quad (4)$$

Energy equation:

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right). \quad (5)$$

Molten solder at high temperature has a nearly constant viscosity (Puttlitz & Stalter 2004) and can thus be described as follows:

Newtonian fluid equation:

$$\eta = \frac{\tau}{\dot{\gamma}}, \quad (6)$$

where τ is the shear stress and $\dot{\gamma}$ is the strain rate.

The volume of fluid (VOF) tracks the flow front during the wave soldering process. The governing equation of melt front over time is governed by the following transport equation (Ramdan *et al* 2012):

$$\frac{dF}{dt} = \frac{\partial F}{\partial t} + \nabla \cdot (uF) = 0, \quad (7)$$

where $F=1$ represents a cell that contains molten solder only (Sn63Pb37), a value between 0 and 1 ($0 < F < 1$) is given in “interface” cells (referred to as melt front of the molten solder), and $F=0$ represented in a grid of molten solder void.

5. FLUENT modeling

A simulation was performed prior to the experimental study to validate the feasibility of the experimental evaluation by comparing the experimental and simulation results. In the experiment, the visualization of the real time PCB hole filling process is difficult due to the tiny size and limited equipment. Therefore, the simulation modeling technique is advantageous to provide the process visualization. Thus, the purpose of simulation analysis is to enrich the understanding of the fluid motion and capillary action of the molten solder. The predicted simulation results are useful for the reference and provide the fundamental knowledge during the wave soldering process. Better understandings of the wave soldering process help the engineer to enhance the process parameter and PCB design, which could minimize the unintended features and defects of the PTH solder joint. A fluid domain of PTH and PCB was modeled in the pre-processing step. The simulation was conducted for a single pin soldered into the PCB hole using the adjustable fountain wave soldering machine at a conveyor angle of 0° . A 3D model was developed, and the meshing and boundary conditions were set by a preprocessor commercial modeling software according to the actual dimensions of the PCB and PTH mentioned in Section 3. The mesh model was built and optimized with 599920 hybrid nodes as shown in figure 9. The bottom and sides of the solder pot, PCB hole, and PTH connector were defined as walls in the boundary condition setup. The top of the solder pot was set as the pressure inlet, whereas the top and bottom of the PCB were defined as the interior and pressure outlet (figure 10). The boundary and initial conditions were as follows.

- (a) On the PCB, the solder pot and components wall: $u = v = w = 0$, $\frac{\partial P}{\partial n} = 0$
- (b) On the melt front: $P = P_{atm} - \Delta P$
- (c) At the outlet: $P_{out} = P_{atm} = 0$

Note: Pressure difference (ΔP) can be expressed by the law of Young and Laplace. ΔP is the pressure difference between the inside and outside of the curved liquid surface, γ is the liquid surface tension, and R_1 and R_2 are the radii of the curvature on liquid surface. Note that R_1 and R_2 are negative because they are outside the liquid.

$$\Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right). \quad (8)$$

Figure 9. Meshed model.

The developed model was exported to FLUENT for fluid analysis. The optimized time-step size employed in the current simulation was 0.0001 s (Abdul Aziz *et al* 2014b). Transient/unsteady calculations were performed in the analysis. A capillary action occurred when the molten solder came into contact with the PCB hole through the soldering process. An implicit VOF method was conducted to track the fluid motions of the two phases (i.e., molten solder and air). The volume fraction was set to 1 for the molten solder and 0 for the air phase. In addition, eutectic Sn63Pb37 was selected as the solder material because of its excellent wetting capability at a low melting temperature (183°C). The material properties are summarized in table 1. A uniform temperature of 250°C was defined as the initial temperature in FLUENT according to the experimental setup.

Figure 10. Boundary conditions setup in the FLUENT modeling.

Table 1. Summarized of eutectic Sn63Pb37 properties (Abdul Aziz *et al* 2014c).

Factor	Value
Viscosity (mPa s)	140
Thermal conductivity (W/m K)	50
Specific heat capacity, C_p (J/kg K)	167
Density (kg/m ³)	8400
Reference temperature (°C)	250

The stability of the melt front was controlled by the following under-relaxation factors: momentum = 0.01, density = 1.0, body forces +1.0, and pressure = 0.3 (Abdul Aziz *et al* 2014c). Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm was defined under pressure velocity coupling with the second-order upwind scheme to solve the governing equations and discretize the volume fraction and momentum and energy equations (Abdul Aziz *et al* 2014c). The simulation results were then compared with the experimental results.

6. Results and discussion

6.1 Validation of the experimental and simulation solder profiles

Figure 11 shows a comparison of the solder profiles from the experimental and simulation results of PTH. Vertical filling levels of 50%, 75%, and 100% were considered in the adjustable fountain wave soldering process (0° conveyor angle) for a 3.1 mm thick PCB. The experimental solder profile was examined through X-ray CT scanning as previously mentioned. The experimental results showed almost uniform solder profiles for each filling level. A slightly convex profile was observed at 75% filling level. A similar phenomenon was also observed in the simulation results (75% filling level). This occurrence may be attributed to the variation in surface tension in the PCB hole. In the VOF model, a volume fraction of 0.5 (Khor *et al* 2012a, 2012b; Balachandran 2012; Yazdi *et al* 2010) is always employed to define the interface of the molten solder. The maximum and minimum levels of the molten solder were estimated for both results and are shown in figure 12. The experimental and simulation results are in reasonable agreement, with only 4.96% and 2.08% discrepancies for the maximum and minimum levels, respectively (figures 13 and 14).

6.2 Effect of PCB thickness

The effect of PCB thickness on the vertical fill for both adjustable fountain (0° conveyor angle) and conventional (6° conveyor angle) wave soldering processes was investigated. The vertical fill for the square pin was considered. Figure 15 shows a comparison of the three selected samples for both wave soldering processes at three different PCB thicknesses (i.e., 1.6, 3.1, and 6.0 mm). The vertical fill of the PCB hole was observed through X-ray CT scanning. The solder material showed an intense color in the X-ray image. The experimental results revealed that PCB thickness significantly affects the vertical fill in both wave soldering processes. An increase in PCB thickness decreases the vertical fill. The samples of the vertical fill of each PCB thickness are summarized in tables 2 and 3. In the adjustable wave soldering process, the vertical fill was 100% (with a topside fillet) at 1.6 mm PCB thickness. Almost 85% of the PCB hole were filled

Figure 11. Comparison of experimental and simulation solder profile at 50% and 75% and 100% filling level (0° conveyor angle and 3.1 mm PCB thickness).

Figure 12. Maximum and minimum filling level.

Figure 13. Minimum filling level.

Figure 14. Maximum filling level.

Figure 15. Vertical fill level (%) of adjustable and conventional wave soldering machine.

Table 2. Average (%) of vertical fill level for adjustable wave soldering machine (square pin).

PCB thickness (mm)	1	2	3	Average
1.6	100.0%	100.0%	100.0%	100.0%
3.1	86.2%	94.5%	72.7%	84.5%
6.0	47.4%	47.4%	47.37%	47.4%

in the PCB with a thickness of 3.1 mm, a value that is considered acceptable for most electronic applications. However, nearly 50% of the PCB hole were filled with molten solder in the PCB with a thickness of 6.0 mm.

Table 3. Average (%) of vertical fill level for conventional wave soldering machine (square pin).

PCB thickness (mm)	1	2	3	Average
1.6	91.0%	91.2%	94.8%	92.3%
3.1	64.8%	55.6%	57.4%	59.3%
6.0	13.7%	29.3%	30.0%	24.3%

Figure 16. Comparison of vertical filling level (%) at different PCB thickness (square pin).

$$Aspect\ ratio\ (AR) = \frac{hole\ diameter,\ d}{PCB\ thickness,\ t}$$

Figure 17. Aspect ratio of the PCB.

Figure 16 shows that conventional wave soldering produced less vertical fill than adjustable fountain wave soldering for all three PCB thicknesses. No topside fillet was found in the PTH solder joint in the 1.6 mm thick PCB. The increase in PCB thickness (3.1 mm) significantly reduced the vertical fill; approximately 60% of the PCB hole were filled with solder. The vertical fill in the 6.0 mm thick PCB was very low (24.3%). This result indicates that the effect of PCB thickness on the performance of vertical fill is enhanced when an adjustable wave soldering method is utilized. The vertical fills for both 3.1 and 6.0 mm thick PCBs are considered defective

because they are lower than the minimum vertical fill of 75% stated in IPC-A-610D. Thus, optimum process setting is important to enhance the vertical fill of thick PCBs. Appropriate process parameters could significantly improve the vertical fill through adjustable fountain wave soldering method.

Besides, the aspect ratio of the PCB was also investigated. Figure 17 shows the aspect ratio of the PCB, which is the hole diameter (d) divided by the PCB thickness (t). The aspect ratio used in the experimental work is summarized in table 4. The experimental results (table 5) revealed the highest vertical fill level when smallest aspect ratio (AR=2) is applied to both types of wave

Table 4. PCB sample at different aspect ratios.

PCB thickness, t (mm)	Hole size, d (mm)	Aspect ratio (AR) (t/d)
1.60	0.80	2
3.10	1.03	3
6.00	1.51	4

Table 5. Average (%) of vertical fill level for adjustable 0° and conventional 6° wave soldering machine s at different AR.

AR	Adjustable 0° (%)	Conventional 6° (%)	Differences (%)
2	100.0	92.3	7.7
3	84.5	59.3	25.2
4	47.4	24.3	23.1

Figure 18. Vertical filling level versus aspect ratio of the PCB for adjustable and conventional wave soldering.

Figure 19. Circular PTH vertical fill using the adjustable wave soldering machine.

soldering process. The vertical fill level is decreasing, when the aspect ratio of the PCB rises to 3 and 4. This indicated that the vertical fill level is crucially affected by the aspect ratio of PCB. The correlation between the percentage of vertical fill and the aspect ratio is illustrated in figure 18. From the results, the application of the adjustable wave soldering improved the vertical fill from the conventional wave soldering nearly 7.7%, 25.2% and 23.1% for the aspect ratio 2, 3 and 4, respectively. The experimental results revealed that application of adjustable wave

Table 6. Average (%) of vertical fill level for adjustable fountain wave soldering (circular pin).

PCB thickness (mm)	1	2	Average
1.6	100%	100%	100%
3.1	90.4%	88.5%	89.5%
6.0	46.8%	50.8%	48.8%

Table 7. Differences of vertical fill level (%) between circular and square pin.

PCB thickness (mm)	Circular	Square	Differences
1.6	100%	100.0%	0%
3.1	89.5%	84.5%	5%
6.0	48.8%	47.4%	1.4%

soldering process yielded better vertical fill than the conventional wave soldering method. Both experimental results were compared at different PCB thicknesses, while the PCB hole diameter and pin shape are considered as constant parameter. As mentioned in Section 3, the adjustable wave soldering machine has different methods to generate the fountain wave, where the solder wave height is adjustable (to improve the contact area with the PCB) compared with the conventional wave soldering machine. In figures 5 and 6, the solder fountain can be controlled based on the PCB specifications. For example, two fountain waves from both pressure nozzles are generated for denser PCB hole, which enhance the contact area of the solder with the bottom PCB. However, the fountain wave height of the conventional wave soldering is difficult to control. Therefore, the experimental results showed better vertical filling compared with the conventional wave soldering machine.

6.3 Effect of pin shape

Figure 19 shows the selected samples of the circular pin solder joint after adjustable wave soldering. A phenomenon similar to the one discussed above was observed when a circular pin was used for PCBs with various thicknesses. The use of a circular pin has a minor effect on vertical fill as shown in table 6. The application of a circular pin produced a vertical fill of 100%, 89.5%, and 48.8% for the 1.6, 3.1, and 6.0 mm thick PCB, respectively. The differences between the square and circular pin in the 3.1 and 6.0 mm thick PCB are only 5% and 1.4%, respectively (table 7). The vertical fill level is plotted against PCB thickness in figure 20. The results show that the shape of the pin does not significantly affect the vertical fill in the adjustable fountain

Figure 20. Average vertical fill level (%) for circular and square pin shape.

Table 8. Average (%) of vertical fill level at different AR for adjustable fountain wave soldering.

AR	Square (%)	Circular (%)
2	100.0	100
3	84.5	89.5
4	47.4	48.8

Figure 21. Vertical filling level versus aspect ratio of the PCB for square and circular pin.

wave soldering process. The use of square and circular pin also influences the vertical fill level for different aspect ratios in the adjustable fountain wave soldering process. The experimental results are summarized in table 8. Both square and circular pin demonstrate highest vertical fill for smallest aspect ratio ($AR=2$). The vertical fill level decreases when the increase in aspect ratio. However, the vertical fill was slightly affected by the pin shape at different aspect ratios. The differences of the vertical fill for both pin shapes are less than 6%. The circular pin has 5% of vertical fill higher than square pin at an aspect ratio ($AR=3$). This scenario is clearly observed in figure 21. Moreover, angle-edged PTH, such as triangular and hexagonal PTH, can affect surface tension and adhesive force, which in turn increase the filling time and result in an uneven profile (Abdul Aziz *et al* 2014c) during wave soldering.

6.4 Voiding in the PTH solder joint

The presence of voids may cause cracks to occur in the solder joint under a thermal cycling condition (Nguyen *et al* 2009). Therefore, minimizing voids in the solder joint is always a concern in the electronics assembly industry. The presence of voids in the PTH solder joint may be attributed to several factors, such as pin-to-hole ratio (Nguyen *et al* 2009), PTH plating, improper conveyor speed, preheating time, and intermetallic outgassing. Typically, the void formation is due to the moisture entrapment, and outgassing during the wave soldering process (Alpha 2011); hence, it forms the void in the PTH solder joint. Besides, too much flux on the PCB that not evaporates (or drying off) during the pre-heating stage leads to the outgassing and creates voids.

Figure 22. Void formation of 1.6 mm PCB thickness.

Other factors such as improper plating of the PCB and poor solderability due to oxidation will also cause the void formation. Therefore, the effect of PCB thickness on the void in the PTH solder joint was also investigated. Figure 22 shows an example of a PTH solder joint (1.6 mm PCB

Figure 23. Void formation of 3.1 mm PCB thickness.

thickness) for the two methods. The arrows point to the void in the solder joint. In the 1.6 mm thick PCB, small voids can be found in regions close to the PCB hole surface. The PTH solder joints of the two wave soldering methods have almost the same void size as shown in figure 22. The experimental results reveal that a thick PCB produces large voids in the PTH solder joints (figure 23). The voids in the conventional wave soldering-assembled PTH (at 3 mm thickness) are larger than those in the PTH soldered by adjustable fountain wave soldering. Figure 24 shows the PTH solder joint of the 6 mm thick PCB assembled by adjustable fountain wave soldering. Small void size was observed around the pin.

Figure 25 shows an experimental sample of an offset pin in the PCB through-hole after wave soldering. The components in the figure are clearly labeled. The void in the solder material formed close to the surface of the PCB hole, and no crack was found around the void region. Figures 26 and 27 show the void and stain found in the sample. The stain of the PCB through-hole was identified and created during sample preparation. The void size depicted in figure 26 is larger than the void size in figure 27. Large voids or excessive numbers of voids may affect the integrity of the solder joint and thus cause failure in the electric connection. Voids may also increase the stress on the solder joint, facilitate crack, and affect the joint's capacity to withstand low cycle fatigue. To eliminate the void formation in the PTH solder joint, a few criteria must be concerned such as contamination in the PCB hole, entrapped fluid by the component, and outgassing of moisture that entrapped in the PCB during the wave soldering (Alpha 2011). Therefore, proper control of several parameters, such as board contamination, oxide content of

Figure 24. Void formation of 6.0 mm PCB thickness for adjustable wave soldering.

Figure 25. Void formation of pin assembly.

the soldered surface, and surface finish of PCB, is important to minimize voids in the PCB through-hole during wave soldering. Several recommendations can be considered during the wave soldering process to attain better soldering quality based on the experimental results. The adjustable fountain wave soldering technique yields better vertical fill compared to the conventional wave soldering machine. This is because high energy fountain wave from the adjustable wave soldering machine improves the vertical filling process. Besides, proper control of dwell time (contact time for molten solder and PCB) and temperature of the topside board is important to obtain better vertical fill, and topside fillet. Soldering temperature plays a crucial role in the vertical filling. Insufficient or too low solder temperature causes the molten solder cool and solidifies in the PCB hole before it reaches the top side, this phenomenon can be observed when

Figure 26. Stain and void formation for offset pin position.

Figure 27. Void formation in PCB through-hole for offset pin position.

using the thicker PCB. Therefore, the control of process parameters is significant to obtain the best quality of PTH solder joint during the wave soldering process.

7. Conclusions

An experimental investigation was conducted on the effects of PCB thickness on adjustable fountain and conventional wave soldering. The PTH vertical fills for 1.6, 3.1, and 6.0 mm PCB thickness were examined with an X-ray CT scan machine. The vertical fill for the three PCB thickness values, the pin shapes, and voiding was discussed. The experimental results reveal that PCB thickness significantly influences vertical fill. An increase in PCB thickness and aspect ratio reduces the percentage of vertical fill. The wave soldering method employed also affects the percentage of vertical fill. Adjustable fountain wave soldering process (0° conveyor angle) yields a higher vertical fill than conventional wave soldering (6° conveyor angle) for all three PCB thickness values. The vertical fills of adjustable fountain wave soldering for thickness of 1.6, 3.1, and 6.0 mm are 100%, 84.5%, and 47.4%, respectively. Vertical fills of only 92.3%, 59.3%, and 24.3% were obtained when conventional wave soldering was employed. The results indicate that a molten solder can easily fill a PCB hole at a conveyor angle of 0° . The differences in vertical fill level for both circular and square when using different PCB thicknesses (1.6 mm, 3.1 mm and 6.0 mm) were 0%, 5% and 1.4%, respectively. Pin shape has an insignificant effect on vertical fill in adjustable fountain wave soldering. The results also reveal the difficulty in obtaining a vertical fill of 100% and the problem of large voids in thick PCBs. The experimental and simulation results show a reasonable agreement, with only 4.96% and 2.08% discrepancies for the maximum and minimum vertical fill levels, respectively, in adjustable fountain wave soldering.

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