Design Improvements for Selective Soldering Assemblies

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Abstract
Selective soldering, along with pin-in-paste reflow and press fit, is the primary assembly method for through-hole components. The reflow process is limited by component dimensions and heat resistance. Press fit becomes expensive when defects that can't be repaired. Electronic manufacturing services realize that SMT can't replace the through-hole technology completely. The selective soldering process offers opportunities to make solder connections on different levels, connecting housings, junction boxes, aluminum parts, stacking PCBs and more. Designers of new board assemblies can benefit from the specialized soldering nozzles and robotics capabilities that modern selective soldering machines offer.

Selective soldering can be achieved under an angle (tilt) as in wave soldering, or horizontally with different shaped nozzles and nozzle materials. All have different properties and can be applied to successfully soldering the most complex assemblies. In order to optimize production and soldering efficiency, assembly engineers should be involved in the Design for Assembly process. Knowledge of the selective soldering process and nozzle technology may offer competitive advantages when implemented in new design and assembly processes.

Studies have been done to determine minimum distances to adjacent components, especially SMDs. Questions asked include 'What pin to hole ratio provides the best hole filling? and 'How much influence has flux selection on soldering results, and which nozzles should be used?' Historical data is combined with several Design of Experiments, looking for soldering defects such as bridging, but also seeking process optimization to achieve the best hole filling. Hole filling is critical for high thermal mass boards. The thick copper layers absorb a great deal of heat from the preheating and liquidous solder. Special design modifications will result in more heat in the solder barrel, which will guide the solder to the solder destination side of the board. In combining the right nozzle selection with correct solder acceleration and deceleration will ensure that even the most difficult to create joints will meet the IPC-A-610 classification.

Introduction
Soldering requirements for PCB assembly have become ever more critical. The automotive industry tends to eliminate repair of soldering defects, which makes it even more important to understand the soldering process and material characteristics in order to avoid excessive waste and costs. Many designs have their roots in wave soldering and defects can be dramatically reduced when some simple improvements are made to enhance compatibility with selective soldering applications. Many defects can be eliminated in the design phase of the assemblies when specific rules for a robust selective soldering process are applied. This includes material selection as well as board design-related properties. This paper details methods of defect prevention through the application of design rules that are made for selective soldering processes using different methods of soldering. These rules includes recommendations for handling the board (placement accuracy, warpage, etc.), dimensions of pads, distances to surrounding SMDs or other components, improving heat transfer to the board by designing special via holes or modified pad structure, and more. The rules are identical for leaded or lead-free applications, although lead-free is more difficult due to the alloy's higher melting point, increased copper leaching, solder contamination, and the greater difficulty in achieving sufficient hole fill.

Issues to be tackled
Selective soldering requires some knowledge of the process. The critical topics are electro-migration (due to excessive flux), bridging, through hole filling (thermal issues) and solder balling.

1. Electro-migration and Selective Soldering

Electro-migration is a potential risk when too much flux is used, or when flux penetrates into areas where it is not activated. The best way to avoid this risk is to clean the board after soldering, or to use a no-clean flux that is inert after soldering even when it has not been heated to high temperatures. The spreading of flux is critical, and the assembly's designer can influence this spread by selecting a proper solder mask and by making barriers that inhibit flux flowing.

Fluxing in a Dip Process

In a multi-wave dip process, all solder joints are formed simultaneously. The pins are dipped into a nozzle of liquidous flowing solder. The flux should remain within the nozzle area. For optimal results, it should not spread further than 0.5 mm inside of the nozzle rim. This liquidous solder will move the flux just enough to remove the thin oxides on the solder. The board designer can influence the flux spreading by selecting a proper solder mask, since the roughness of the solder mask is important in controlling this spread. A surface energy of 35 mN/m^2 is the best number where for wave soldering the values were >45 mN/m^2 in order to make the flux spread sufficiently. Also, there must be a free area of another 1 mm to the surrounding SMT components to make soldering possible. Some designers mark dedicated colored areas on the board where the through-holes are located for dipping.

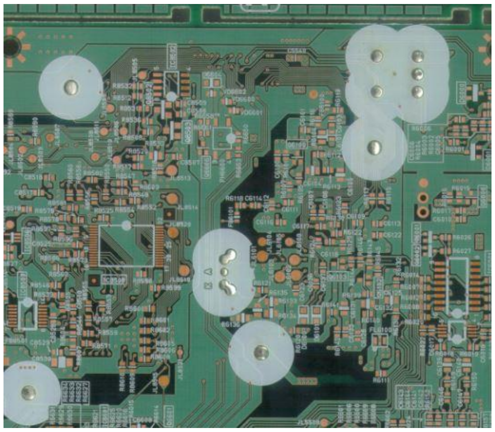

Figure 1 – Selectively soldered PCB with white areas where solder joints are located.

In **Figure 1,** the white-colored areas are easy to recognize for inspection, but also these areas could have a different surface energy to avoid flux spreading. Furthermore, it is easy to recognize solder webbing, e.g., excessive solder and dross that sticks to the PCB when the board touches the nozzle rim, solder balls, and bridging.

2. Through-hole Barrel Dimensions

Three factors are important in order to create a good solder joint; heat, time (dwell), and mass. The following experiment shows how important it is to have enough space and an accurate soldering machine to make soldering successful. The heat in the soldering process is the solder temperature together with preheating. Time is the contact time between the lead, solder and board material, i.e., those parts that need to be connected. The mass of the pin can be very critical if there is only small space for a nozzle and the lead itself absorbs a lot of heat. Solder in a small nozzle may even freeze if the pin sucks all the heat out of it.

This experiment focuses on contact time, which is defined as the time that the solder pin and pad (that need to be joined together) are touching the liquidous solder. Some commercial devices available on the market measure this time. In this experiment, a data logger wave measurement is used, utilizing a 0.5 mm pin to measure contact with the alloy. When a pin is soldered using a small nozzle, the longest contact time is achieved when the pin is in the center of the nozzle. For a two-row connector, however, this is not the case. For some assemblies, where there is not enough space, the pin may also be outside of the center of the solder. This experiment will quantify the impact of being out-of-center. Another parameter in soldering is immersion depth, i.e., how deeply the board is immersed in the wave. For example, when the wave just touches the bottom of the assembly, the immersion depth is 0. Lowering the board for 1 mm creates an immersion depth of 1 mm, and so forth. In

wave soldering, the golden rule is to have the immersion depth 0.5 x board thickness. For PCBs that are 1.6 mm thick, this would be 0.8 mm. In this experiment, the board was soldered at 1.00 mm and 1.50 mm immersion depth, respectively.
During selective soldering a board may warp. Board warpage compensation is a machine option that changes the solder pot height in order to maintain the same immersion depth over the complete assembly even when the board warps. The final parameter that controls the contact time is the drag speed of the solder pot. The pot moves with a defined speed beneath the assembly. In this experiment, 2 and 3 mm/sec. were compared.

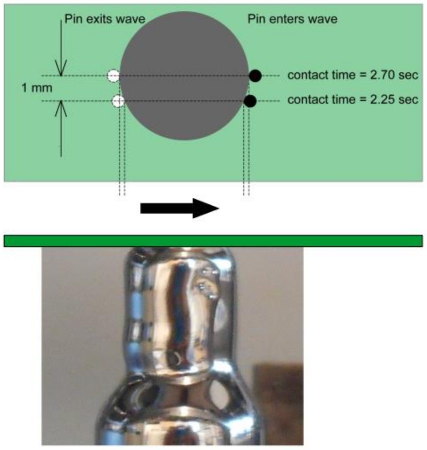

Figure 2: The impact of soldering out of center: shorter contact time for the pins.

Figure 2 illustrates an example wherein all solder conditions are identical. Due to the fact that the pin is 1mm off the center of the wettable nozzle, contact time is reduced by17%. The parameters and levels of the design of experiments is summarized as follows:

Table1: Design of experiment contact time and heat transfer

Parameter	**Unit**	**Level 1**	**Level 2**
Pin position		Center nozzle	Offset 1mm
Immersion depth	[mm]	1.0	1.5
Solder pot speed	[mm/s]	2.0	3.0

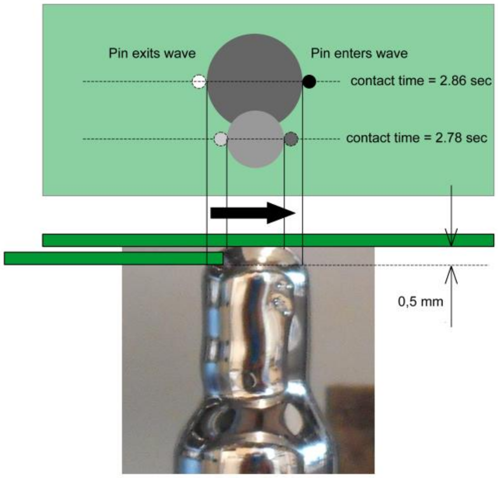

Figure 3: The impact the immersion depth – deeper in the solder longer contact.

Figure 3 illustrates an example wherein all solder conditions are identical. If the immersion depth increases 0.5 mm more, the contact time increases with 0.08 seconds for this wettable nozzle. The difference in this instance is only 3%.

Soldering is repeated 10 times for each setting, and the averages are analyzed. The best way to visualize the impact of the individual parameters is to create a Factorial Plot. The plot for the 6 mm non-wettable nozzle (solder flowing to the front side) indicates that the impact of the drag speed of the solder pot has the most influence on contact time. Due to the shape of the liquidous solder column, the contact time is reduced by 15% when the pins are 1 mm off center. Immersion depth (1.00 versus 1.5 mm) has no significant impact; only 1%. This makes the process robust, since a slight warpage of the board will not affect soldering results.

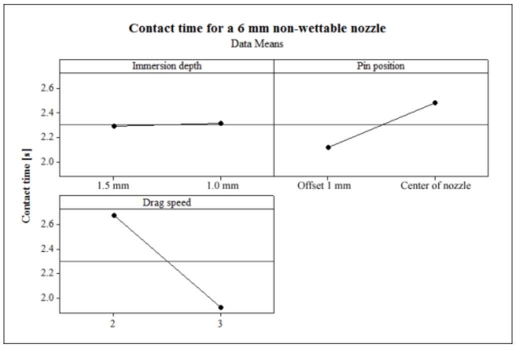

Figure 4: Factorial Plot of 6 mm non-wettable nozzle, showing the effect of parameters on contact time.

For a wettable nozzle, with solder is overflowing on all sides (see **Figure 2**), the results are slightly different. Because this nozzle has an 8 mm round shape, the influence of the pin position is less significant and the immersion depth becomes more critical. Contact times are longer due to the wider diameter. The average contact time is 3.6 seconds versus 2.3 seconds for the 6mm non-wettable nozzle.

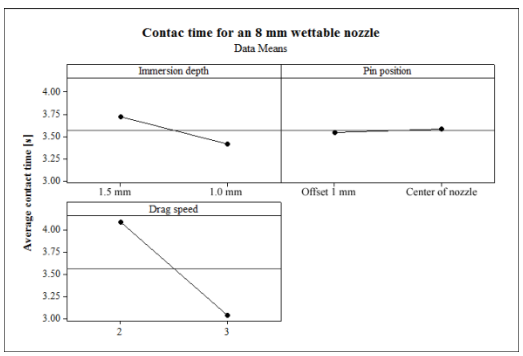

Figure 5: Factorial Plot of 8 mm wettable nozzle, showing the effect of parameters on contact time.

To achieve sufficient hole filling, it is important that the pin *and* its diameter are compatible with one another. There should be enough space for the solder to flow through, and yet not too much space, because it is not possible to solder air! In the next experiment, hole filling is studied for different nozzles and barrel configurations. Hole diameter is an important parameter, where the pad diameter is critical for bridging. On an 8-layer 2.4 mm thick FR-4 board, a 64-pin connector was soldered. The board utilized different hole and pad diameters to enable the study of hole filling. Both wettable and non-wettable nozzles were used and inspected with an X-ray machine. The pin diameter is 0.65 mm and the pins have a 2.54 mm pitch. After fluxing, the board was preheated with IR lamps to a top side temperature of 115 ºC. The solder temperature was 300 ºC and the drag speed was 2 mm/s.

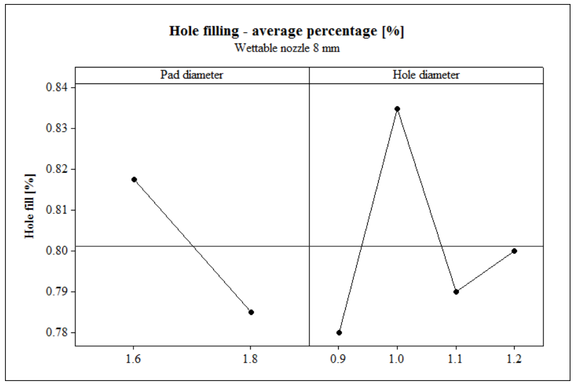

Figure 6: Hole filling [%] for an 8 mm wettable nozzle.

The same experiment was repeated for a 6 mm non-wettable nozzle. This nozzle had a much smaller wave. There is less solder contacting the PCB, and therefore hole filling is minimal due to less heat transfer.

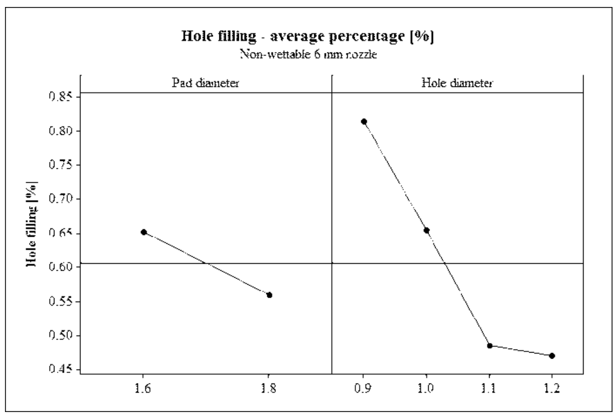

Figure 7: Hole filling [%] for a 6 mm non-wettable nozzle

Although the nozzle is smaller and less solder will flow to the pin, the same hole fill can be achieved when the design of the barrel is optimal. As a general rule, hole diameter is pin diameter + 0.4 mm.
Previous experiments investigated the reliability of the solder joint for different hole and pad diameters. Tensile strength is measured by pulling the pins out of the soldered barrel. For SAC 305, the data is listed in the following table:

Table 2: Average Tensile force [N] for different diameter holes

	0.9mm	1.0mm	1.1mm	1.2mm
Post soldering	193	198	187	194
500 h aging at 125 ºC	188	173	174	169
1000 h aging at 125 ºC	Not available	166	172	169

From reliability scores, we see that there is no preferred barrel dimension. After 1000 hours of aging, all scores are within 5% and the strength is still approximately 10 times stronger than SMT.

Another potential risk in selective soldering is pad lifting. The mismatch of the materials (Copper barrel, FR-4 board material and solder) may result in fillet or pad lifting. Fillet lifting (separation between solder and pad) is less critical than pad lifting. Pad lifting (see **Figure 8)** is a defect according to IPC-A-610F.

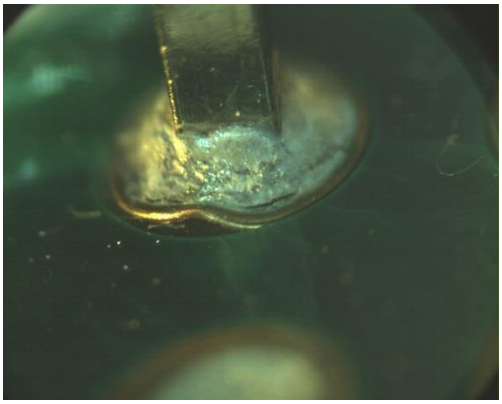

Figure 8: Pad lifting

The designer should select a smaller pad diameter for the solder destination side to minimize the risk of pad lifting. The solder temperature should be as low as possible to reduce the risk of this type of defect. Some applications require a high solder temperature due to the copper layers that act like heat sinks. The heat should remain in the soldering area. The task for the designer is to create thermal reliefs on those spots where the heat tends to drift.

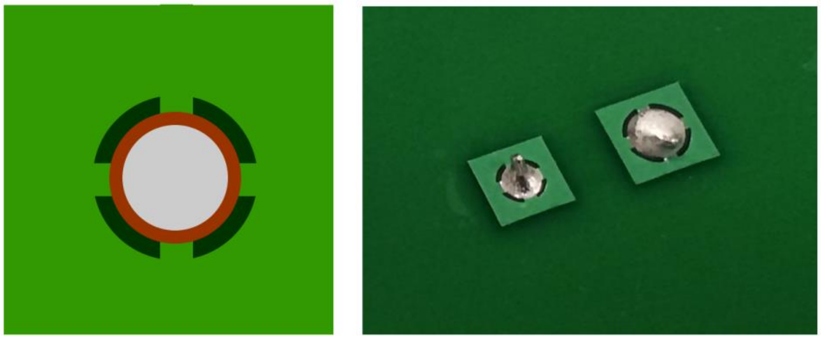

Figure 9: Thermal relief and solder mask

3. Eliminate bridges by improving design

The next experiment will show the impact of pad design on bridging. In this experiment, the PCB assembly is soldered in a multi-wave dip process. In this process, the PCB is moved to a solder pot that contains a number of nozzles that correspond to the THT connectors. In one dip all connectors are soldered. The test board that is used features different pad dimensions for various components from 2.54 mm to 1.00 mm. In this dip soldering experiment, a 20 pin connector is soldered. Solder temperature was fixed at 300 ºC. The board finish is HAL SN100C.

Table 3: Design of Experiment dip soldering

Parameter	Unit	Level 1	Level 2	Level 3
Flux robot speed	[mm/s]	25	225	-
Flux dropjet frequency	[Hz]	50	200	-
Topside board temperature	[ºC]	110	150	-
Pad diameter	[mm]	1.4	1.9	2.4
Component finish	-	Au	Sn	-

After soldering, boards are visually inspected. The number of bridges is counted and the average is plotted in the graph. It is remarkable that none of the selected parameters has a significant impact on bridging, except pad diameter.

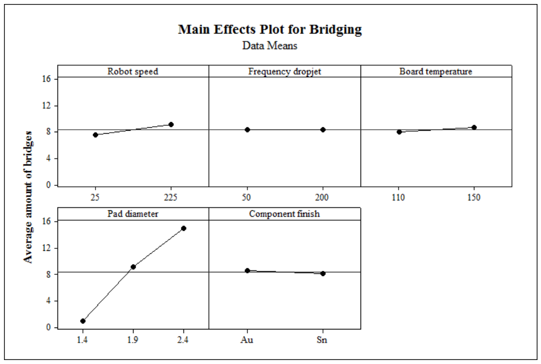

Figure 10: The smaller the pad on the solder side, the less bridging

The risk of bridging depends on the pitch of the leads, their protrusion length, and pad diameter. Since the protrusion length is fixed (3 mm – 1.6 mm board thickness = 1.4 mm) and the pitch is 2.54 mm, the diameter is the parameter that defines whether or not bridging will occur.

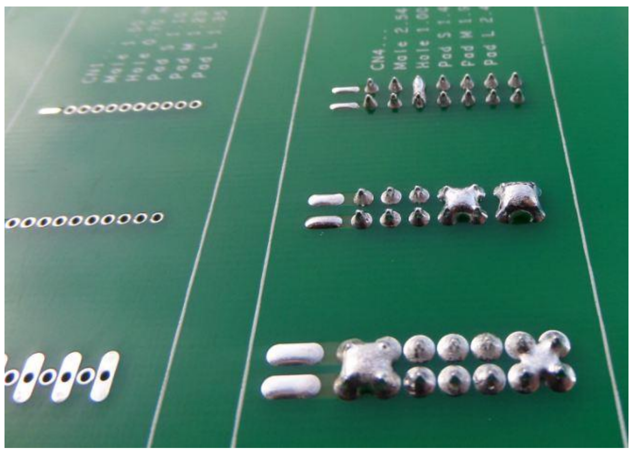

Figure 11: pad diameters 2.4, 1.9 and 1.4 mm and its sensitivity for bridges.

With the right settings for dipping and a strong flux, it is possible to dip solder these components bridge-free without using dedicated tools like screens or wettable strips. **Figure 11** shows the 'solder thieves', but several experiments showed that solder thieves in lead-free applications result in more defects because the solder sticks to the board and solidifies early due to less superheat (i.e., the difference between solder temperature and melting point) compared to leaded assemblies.
Designers can make some small modifications on the board that may result in less bridging.

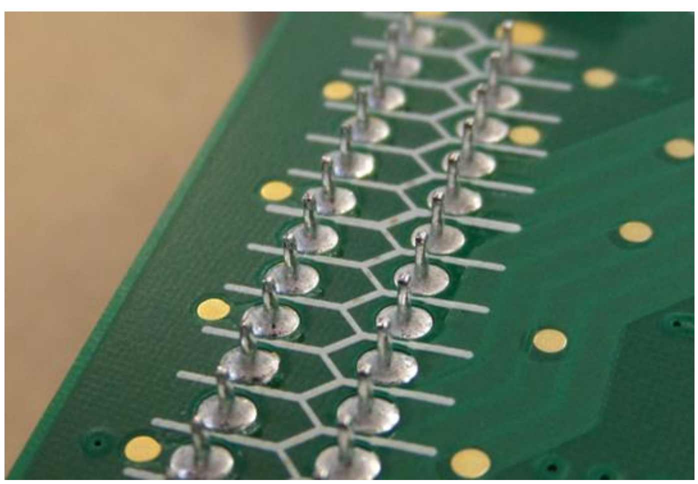

Figure 12: Dedicated silkscreened lines break the capillary force of the solder and discourage bridging

4. Free space and risk of re-melting

The spacing between components is growing smaller. The minimum distance between the pad to be soldered and the next SMT component is defined as 0.5 mm.

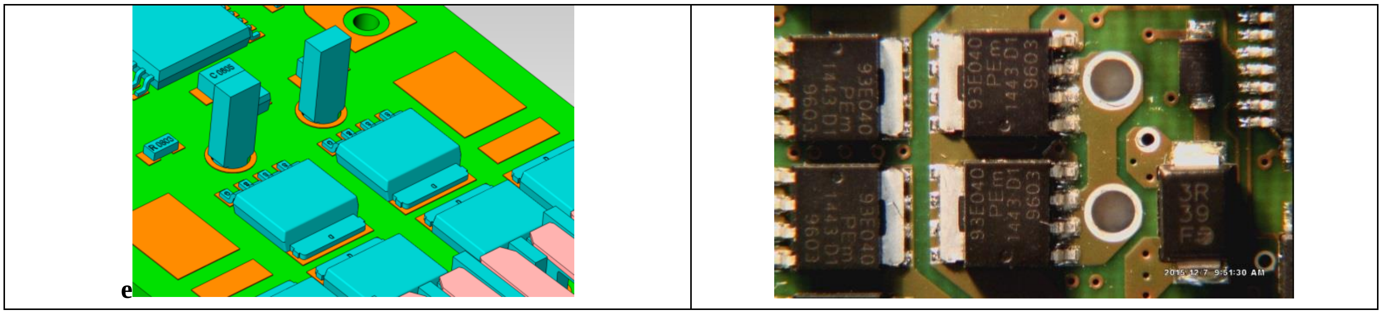

Figure 13: D-Pak with leads 0.5 mm from the barrel on the solder destination side

Selective soldering without touching the surrounded SMT components is feasible when the distance is > 0.5 mm. Small distances often require small nozzle diameters that have less thermal power. For the assembly above, it might be a critical issue that the lead is getting so much heat from the nozzle that the solder paste underneath may re-melt. For this type of component (D-Pak), re-melting of one lead is still acceptable if the solder paste remains on the pad and the solder connection is not affected after solidification. If the paste wicks away from the pad, the joint might not pass IPC-A-610F. Solder wicking only takes place if there is a hot area where the solder can flow to. In order to verify temperature and prevent overheating of the leads, a thermocouple measures the temperature on top of the lead during selective soldering. The pin is dipped into a 4 and 8 mm wettable nozzle and the temperatures are compared.

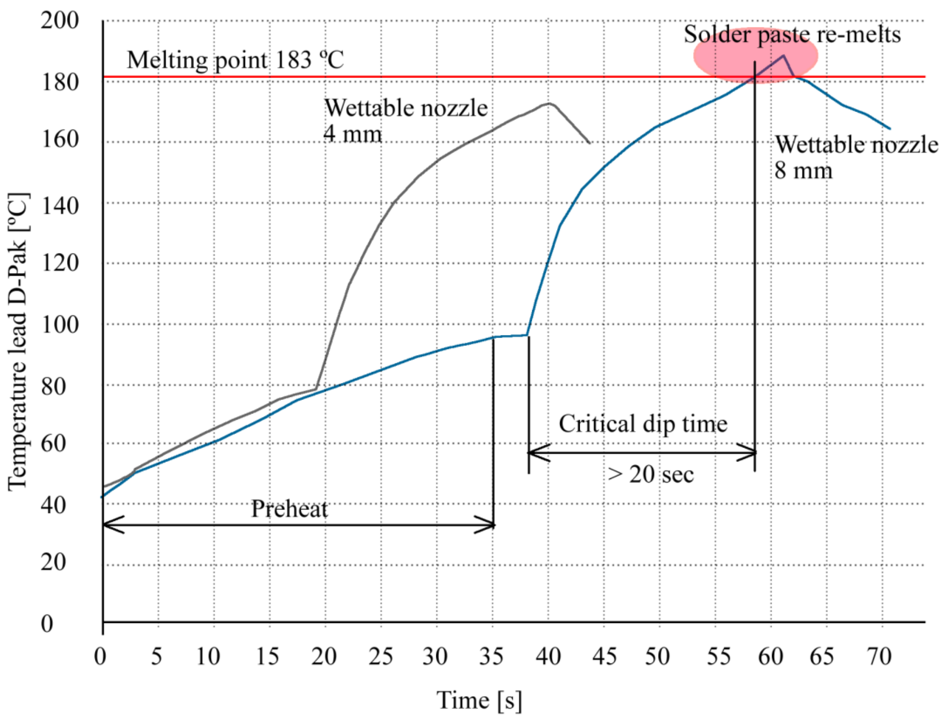

Figure 14: Even with an 8 mm wettable nozzle, it takes more than 20 seconds to re-melt the solder paste

In this experiment, the solder temperature was 330 ºC. Even with this high temperature and only 0.5 mm from the SMT component, no re-melting takes place during selective soldering for this assembly. A dipping time of 5 to 10 seconds is absolutely the maximum for this application. Longer dipping times will not improve the through-hole filling and will only damage the assembly materials.

Conclusion

A selective soldering process can achieve high yields when careful attention is paid to the design requirements during the design phase of the assembly. The design engineer must be aware of these rules:

- Select a proper solder mask to avoid excessive flux spreading and to reduce solder balling;
- Design thermal reliefs for copper layers to keep the heat confined to the solder area;
- Minimize board warpage through symmetric design of copper layers/thermal mass;
- Select small pad diameters to avoid bridging and minimize the risk of pad or fillet lifting;
- Apply silkscreened lines between leads where necessary, to inhibit bridging;
- Thick pin connectors absorb more heat, and therefore require more space and thus a larger nozzle.

References

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