Surface Mount Technology (SMT)
Failure Analysis of Solder Joints and Remedies

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3D Digital Microscope

Now You can See!

As a pioneer of image observation, we have produced a digital microscope that provides answers. It has evolved from a “machine” that simply observes to a “partner” for the observer.

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Summary

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1) Reflow

1) Temperature profile

One of the key factors of reflow oven is preheating. The preheating of a component and PCB is basically the same in leaded and lead-free soldering. Preheating is the range from room temperature to the melting point of solder.

Wettability of solder is influenced by the properties of flux contained in solder as well as the length of time between room temperature and melting point of solder. Most solder failures occur at the melting point. Therefore, a moderate gradient from room temperature to the melting point is a remedy for preventing many solder failures.

Flux properly reacts to heat on component leads. Solder spreads as normal and prevents bridges.

Wrong profile causes deterioration of flux and leads to solder bridges between leads. Bridges and voids occur as flux improperly moves while the solder melts.

Flux reacts with heat first on an entire mounted PCB. Under the normal profile, flux reacts on component leads. Thus, observation of residual flux is important.

Recap: Delta T must be minimized during solder melting phase (as shown with red arrow) but not necessarily pre-heating (as shown with blue arrow).

Preparation of temperature profiles

Solder does not wet unless it melts. Therefore, the temperature difference between leads (Delta T) should be minimized within the tolerance range during solder being melted, but not necessarily during the pre-heat stage. Minimizing Delta T in the pre-heat stage can lead to a greater Delta T within a solder melting temperature, possibly resulting in longer heating or stronger convection, a direct cause of flux burnout and thermal stress on PCBs and components.

Recap: Delta T must be minimized during solder melting phase (as shown with red arrow) but not necessarily pre-heating (as shown with blue arrow).

Wettability is determined during the temperature increase from room temperature to the melting point of solder.

2) Self-alignment effect

If the temperature profile is appropriate and matches the flux properties, bridging and mis-alignment will not occur due to lead-free solder’s strong self-alignment characteristics.

Components are intentionally shifted after mounting and reflow. Due to self-alignment nature of lead-free solder, all components are positioned normally on the lands through the reflow process.

Shifted QFP is re-positioned because of self-alignment effect.
Even with a good temperature profile, self-alignment will not occur if there is insufficient solder printed. A proper amount of solder is required to take advantage of the self-alignment effect.

**Printing solder on resist**
Solder on resist area flows and coheres to component leads as shown in pictures 17 and 18. During mass production, aperture (shown with red line) allows a consistent solder print. Printing high volumes using a mask opening (as shown in the red dotted line) is more reliable than applying solder by hand. The key point for good printing is to print the solder thin and wide to the resist line in order to allow sufficient heat transfer.

**3) Reflow of applied solder**

Instead of manual application, solder can be applied by reflow due to the cohesive nature of lead-free solders.

**4) Reflow of through-hole parts**
Through-hole parts can be done by reflow. Reflow minimizes soldering inconsistencies that often occur with a manual soldering process. The use of reflow instead of flow is environmentally friendly and improves cost performance and quality.

Selection of solder and printing conditions are key factors to determine solderability:

- Residual flux found on both sides of the through-hole is an indication of good soldering.
- No bridges despite leads inserted from the bottom side. (Pictures 26 and 28)

Printing side and insertion direction of leads are at manufacturer’s discretion. Thin and well-spaced solder printing allows flux to react to heat. Flux needs to react to heat quickly and stay within the printed area.
Examples of incorrect soldering

Picture 29

Combining the printed solder with the land increases thickness, resulting in slower heat reaction and a higher risk of bridge formation.

Picture 32

Using higher temperature resistant flux causes spattering. The selection of solder (flux) is extremely important in order to prevent bridges from forming and/or insufficient solder which can cause voids to occur more frequently.

Picture 35

Long leads have a high convective flow that reduces the risk of voids.

5) Flux characteristics

Picture 37

The temperature at the tips of the leads is lower due to the solder melting temperature and the flux vaporization overlapping, and/or the residual high temperature resistant flux repelling the solder.

Picture 40

In these pictures of solder and residual flux on an FPC, there is a significant amount of residual high temperature resistant flux. This leads to voids on the bottom of fillets. (Pictures courtesy of Yuyama Co. Ltd.)

Picture 43

Although they look like fibers or hair, these pictures show residual flux. The location of this phenomenon cannot be specified.

Picture 46

Some of the solder oxidizes and does not melt because of spattering flux. This leads to voids on the bottom of the BGA.
Soldier is printed on the FPC resist, quickly connected and placed in the oven. When the first FPC leaves the oven, the oven is turned off, the cover opened and the FPC removed. At this point, the order of the oven heating elements, the temperature profile and the FPC order are recorded. The spattering of solder and flux is checked afterwards.

The photographs show that a significant amount of temperature resistant flux did not evaporate and remain on the FPC and around the solder. If the heat is not properly balanced, this causes voids on the bottom of the FPC. (Picture 50, 51, 52) This is also true for a rigid circuit board. Solder from Company A (Picture 49, 51) on the board does not melt, but solder from Company B (Picture 50, 52) has melted. Even if the metals are the same, different flux (solvents, etc.) have different melting points. Solder from Company A requires higher temperatures and is not appropriate for parts or boards with low temperature resistance.

Residual wire solder using high temperature resistant flux and blowholes.

Using lead-free solder requires working at even higher temperatures, which also require the use of high temperature resistant flux. This creates a cycle requiring higher heating capacity of equipment and tools. Using higher temperature resistant flux has an effect on quality in areas that are not directly visible. This means that production facilities need to re-evaluate their systems for observing and monitoring soldering quality. The KH-7700 digital microscope from Hirox can observe from any angle by rotating the tip of the lens and is perfect for visual inspections at factories. Automated visual inspection machinery alone is not sufficient for determining how to improve production processes. All of the pictures in this pamphlet were taken with the KH-7700 or KH-1300 digital microscopes from Hirox.

(2) Transition of Heat

Heat flows to the interior layers of multi-layered boards. To prevent this, infrared heaters are used to heat the boards themselves and reduce air movement. Then heat is supplied to the leads with an air heater to melt the solder. With convection ovens, fans are used as little as possible during preheating and adjustments must be made to lengthen the main heating time of the profile. Strong air flow has a large impact on the heat of the board and the parts. Low air flow with high temperature resistant flux can result in voids and insufficient heat. When using IR and convection reflow ovens, IR on the bottom of the oven is set high to heat the boards themselves while the heating elements on the top control the melting of solder. A strong fan in an convection reflow oven causes flux and solder to spatter. (Picture 56, 57)

(3) Reflow oven properties and methods of operation

(1) Selecting a reflow oven

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(2) Transition of Heat

Even though the IR heater on the bottom does not provide heat directly to the components, heat from the board passes through the pattern and concentrates around the bottom of the land and partially melts the solder. (Picture 56, 57) The opposite is true with robot soldering. Heat escapes from the pattern and immediate cooling creates good gloss on the FPC. (Picture 57) Also, since flux deteriorates quickly on ceramic boards, solder wetting is achieved by heat from the bottom heater causing the flux to spread to the land first. (Picture 56)

Although heat from air reflow causes the flux to deteriorate first, wide wetting can be achieved without flux deterioration by using the effects of floor heating from the IR heating element.
Long profiles cause flux to deteriorate, creating voids.

Using an IR oven on the bottom helps reduce voids; a common problem with BGA.

Thick solder bridges and un-melted solder occur even after a strong flow of heated air is added in a short period of time due to flux deterioration and the oxidation of particles. The upper heater is appropriately set to melt the solder. More important is preventing the deterioration of flux and solder particles during the preheating stage. Strong air flow during preheating works like an electric fan, causing flux deterioration and oxidizing solder particles, which inhibits melting. Controlling heated air in the preheater allows the solder to melt, even with a lower temperature.

**Mounting of BGA's**

Even with BGA's, if the upper heaters are set too high, oxidation of the ball exterior and deterioration of flux and the components occur and can result in warped bridges and potato-shaped solder.

Halation on the center of the solder ball shows horizontal straight joints, proving that the ball has a good spherical shape. Wettability can be effectively achieved by selecting a profile that suits the characteristics of the solder flux used with N2. If you review the preheating process, you can eliminate the use of N2 by setting the temperature of the bottom heater 20 degrees above the upper heater. By using the bottom heater, you can achieve good wettability without using N2.

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Using N2 speeds set too high.

Using an IR oven on the bottom helps reduce voids; a common problem with BGA.

Long profiles or convection reflow leaves voids on the interior of the fillets due to deteriorating flux and gases emitted when the flow of solder is poor.
Gas does not bleed well from components such as aluminum electrolytic capacitors. Making the lands bigger to facilitate the release of gas from these parts with solder convection helps to alleviate this problem.

After 1000 heat cycles, the solder on the leads has been strongly affected by heat. However, the effect of heat on the front fillet is hardly visible, thanks to the release of heat from the land surface.

The void on the part contacting the lead has a high possibility of cracked solder due to heat from the lead that causes repeated expansion and contraction. It can be assumed that the land surface and the voids in the center of the solder are not affected due to heat dissipation.

Side balls are basically a problem related to the amount of printed solder. However, with lead-free solder, the amount of printed solder should not be significantly reduced, as reductions have an effect on wettability. Instead, the ratio of the land to the opening in the solder mask should be over 100%.

Some solutions to address side balls include:

- **Replacing with bigger land**
- **Increasing the land to opening ratio**
- **Improving solder convection**

**Side balls (on chip side)**

Side balls are caused by misalignment of the part lead surface and the land surface (design fault).

Instead of trying to resolve this by slowing down the conveyor belt, speeding up the belt helps prevent insufficient wicking (Picture 101, 104).
Reducing the amount of printed solder also reduces the amount of flux and inhibits the melting of the solder. The amount of heat at the preheating stage must be controlled, especially with the 0402 chip. However, temperature cannot simply be reduced because there are other parts to be mounted.

The solder on the left land of the 0603 chip did not melt because there was an insufficient amount. With the 0402, self-alignment works to correct misaligned mounts.

When simultaneously mounting parts with different amounts of solder and heat balances, a bottom side infrared heater can be used to provide heat directly to the circuit boards without having an effect on the parts on the bottom. The upper heater controls the melting of solder and prevents deterioration. Excluding special circumstances, the top temperature needed to melt solder is between 230 and 235 degrees Celsius.

If the plating on the part lead tips is insufficient, bubbling solder will wick up between leads and create bridges.

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II. Flow

1) Angle of delivery

The biggest problem with lead-free flow can be seen on the mounting surface. The contact surface of the board and the solder is limited because the angle of the board on the belt is set at 5 degrees. This results in insufficient heat, which can be prevented by increasing the temperature of the solder pots.

Although flux has already deteriorated during preheating, hot air is blown by the first jets. After deterioration, cooled solder with a reduced flow reverts in the second pot. The remaining flux then adjusts the fillet.

This is an irrational mounting method from the viewpoint of flux. The problems with this method are summarized below.
- The board delivery angle is too great
- Application of flux is not uniform
- Insufficient wetting at the through hole through all board layers
- Inappropriate land design
- Insufficient wetting from the through hole due to insufficient heat at a result of heat dissipating from a solid land

Amount of heat = Temperature x time x contact surface

Delivery angle of 5 degrees

Delivery angle of 3 degrees

When flux has been correctly supplied, the status of the applied solder changes by controlling the amount of heat.

Excessive heat =
- (1) Lead is too long
- (2) Temperature in the solder pot is too high
- (3) Speed of conveyor belt is too slow
- (4) Contact surface between the board and the solder is too large

When the delivery angle is 3 degrees, initial heat is supplied. When the delivery angle is 5 degrees, insufficient heat causes the jet lead to quickly break away from the solder pot.

When the delivery angle is 5 degrees, the contact surface between the board and the solder is over twice that of a delivery angle of 3 degrees.

When the delivery angle is 3 degrees, break away time from the solder pots is slow and sufficient heat is supplied.

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If the flux is effective, setting the delivery angle of the board to 3 degrees creates a large contact surface between the board and the solder. Supplying a large amount of heat without increasing the temperature in the solder pots improves the wetting at through holes through all layers of the board and reduces bridges. In order to stop flux from softening and flowing in response to heat, the ability of flux to flow from the solder pot to the board must be maintained. Solder balls break away with excessive heat, and a lack of heat controls solder flow and hardens the balls. (Picture 120, 121)

Unused lands from mistakes in the design can often lead to bridges. With square unused lands, the edges of wetted solder becomes a bridge between leads. This problem can be alleviated by changing the roundness of the solder so the highest point is separated from the lead. Bridges caused by board warping can be prevented by increasing the speed of the conveyor belt so the solder concentrates around the center of the connector lead. In this situation, switch to regular lead-solder flux if the reaction of flux cannot be controlled.

With normal flow solder, a large amount of heat causes dendrite formation and shrinkage cavities. (Picture 123) If the conditions are good, lead-free solder will not produce shrinking cavities. Setting the conveyor belt speed over 1.7 m/minute alleviates the problems of shrinkage cavities and dendrite formation. This depends on the abilities of onsite personnel. (Picture 124, 125)

Roundness at the through hole requires both the temperature at the top of the hole to be higher than the solder melting point and the presence of effective flux. With sufficient heat and appropriate flux, solder wicks up to the top of the lead. Lead-free solder will have a gloss similar to that of eutectic solder.

Unused lands as shown in the red box, can lead to bridges. The highest point of the solder is far from the land as shown in the red box.

Unused lands from mistakes in the design can often lead to bridges. With square unused lands, the edges of wetted solder becomes a bridge between leads. This problem can be alleviated by changing the roundness of the solder so the highest point is separated from the lead. Bridges caused by board warping can be prevented by increasing the speed of the conveyor belt so the solder concentrates around the center of the connector lead. In this situation, switch to regular lead-solder flux if the reaction of flux cannot be controlled.

CONDITIONS

Temperature

(1) Temperature at the top of the hole should be higher than the solder melting point.
(2) If the temperature at the top of the lead is higher than the melting point of the solder, the fillet becomes higher.
(3) The larger the bottom of the land is, the easier it is to transfer heat.
(4) A smaller land at the top of the hole controls heat dissipation more effectively.

(1) Place the unused land so that the center of the land is further separated from the lead and behind the flow of the board to eliminate bridges caused by solder surface tension.
(2) Design so the solder concentrates around one point of the lead.
III. Rework and repair

1) Shiny solder joint

The most important points to consider when using wire solder are the tip shape of the soldering iron, the plating of the tip and the process of adding solder.

![Picture 1: A good, shiny solder joint resulting from even heat dissipation on the land.](image1)

![Picture 2: A glossy fillet only on the land is a result of rapid cooling of the land.](image2)

![Picture 3: Dendrite formation due to slow cooling.](image3)

![Picture 4: Insufficient through hole wetting](image4)

2) Soldering iron tip shape

Heat balance has a major impact on land pattern design during reflow and hand soldering with wire solder. The inner levels of multi-layer boards may experience problems related to either heat dissipation or heat absorption. These issues are easily managed in reflow by the use of infrared heat. However, manual soldering requires work to be done rapidly in order to provide enough heat to the area. Adding excessive heat causes potato-shaped solder joints and insufficient wetting because of flux deterioration and the majority of the heat taking a long time to pass through the land pattern and into the board. A basic rule for both reflow and manual soldering is the application of solder at high temperature for a short period of time to parts with low heat resistance.

![Picture 5: Air bubbles are visible in the residual flux because the soldering iron tip was too small to provide sufficient heat. A void is likely in the through hole.](image5)

3) Repair

Through hole corrections cannot be made by adding solder on to the part surface because the added and old solder in the hole may not melt together. Solder wets to the part surface by providing additional flux on to the part surface and applying heat using a forked tip iron from the lead side to melt the solder.

![Picture 6: Insufficient through hole wetting](image6)

![Picture 7: Lead surface is good](image7)

![Picture 8: Re-apply heat to the lead surface](image8)

4) Defects due to insufficient soldering leaving a residue of poorly activated flux

Air bubbles are visible in the residual flux because the soldering iron tip was too small to provide sufficient heat. A void is likely in the through hole.

![Picture 9: Differences in fillets created when applying solder numerous times with a small soldering iron tip to a large land.](image9)
The Hirox KH-7700 digital microscope allows for observation of halation by rotating the lens to change the angle of observation. This method can be used to check the status of residual flux. (MXG-5040RZ lens) In this case, the presence or absence of residual flux also indicates the presence of absence of land stripping.

Although a technician performed the tasks, the work has not been checked carefully. Although boards are normally judged by observing the condition of residual flux, most observation equipment lacks a powerful light source to show the differences. The KH-7700 Hirox digital microscope uses a metal-halide lamp that is very bright and provides numerous lighting options.

2) Observation angle

Changing the angle of observation gives a different view of the same land. (Pictures 163 and 164)

The holes in the side of the land indicate that a long preheating phase caused solder particles to oxidize. The result is unready solder balls that lost fluidity due to flux deterioration and were not attracted to the fillet. This problem can be solved by shortening the preheating phase.

IV. Inspection Process

1) Observation points and remedies

(1) Voids and blowholes

2) Land stripping

Although boards are normally judged by observing the condition of residual flux, most observation equipment lacks a powerful light source to show the differences. The KH-7700 Hirox digital microscope uses a metal-halide lamp that is very bright and provides numerous lighting options.
Changing the angle of observation and the lighting during observation allows the checking of residual flux and joints. In picture 172, the lighting and the angle of observation do not show the true picture.

Rotating the lens and recording video, functions both available with the Hirox KH-7700 digital microscope, enhances observation. Normally, observations are made by first specifying an area for observation with optical equipment and then using a SEM, especially when observing whiskers. Microscopes that can observe the leads deep on the board while recording video are extremely important tools for observation.

3) Observation of whiskers

Rotating the lens and recording video, functions both available with the Hirox KH-7700 digital microscope, enhances observation. Normally, observations are made by first specifying an area for observation with optical equipment and then using a SEM, especially when observing whiskers. Microscopes that can observe the leads deep on the board while recording video are extremely important tools for observation.

4) Other problems

Picture 177 shows a defect where heat from solid lands and holes caused the left side of the chip to melt first. Picture 178 shows a defect where the bottom land oxidized and repelled the solder.

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V. Design

Below are pictures of a working 15 year old TV that we took apart. The parts repaired by hand, using lead solder, were not significantly affected by heat. Yet the repairs are of poor quality. Moreover, although the QFP flow is problematic, they too have not been affected by heat. However, parts that have been affected by heat are clearly broken.

Looking at break downs in recent electronics, many are related to soldering. Most of these products were 10 years old and out of warranty.

It is better, from a business perspective, for future design to be focused not on unreasonably extending the life of a product, but on making sure that defects appear during a prescribed period of time. There is a difference between defects and break downs.
On circuit boards, flux reacts the quickest to heat. Therefore, observations made at the factory should look at the condition of residual flux to analyze and judge the balance of heat. This is the easiest way to eliminate defects.

Finding and fixing defects at the end of or after the whole process is too late. It is better to have the factory personnel curb problems by making an initial analysis before and immediately after reflow. Compared with leaded reflow soldering, failure ratio of lead-free reflow soldering is reduced rather quickly to 10 ppm or less. The point lies in the separate usage of upper and lower heaters that can create temperature differences to match the characteristics of flux and the movement of heat. In an oven that uses both far infrared and air heaters, the upper heater provides enough heat to melt the solder while the far infrared acts like a floor heater, providing even more heat directly to the board from the bottom. This prevents the deterioration of flux and allows parts with different heat capacities to be mounted simultaneously. This is possible even with small reflow ovens by adjusting the speed of the conveyor belt. Larger ovens require faster belt speeds and therefore hot air blows between the components, preventing proper heat balance. This is especially true in the preheating stage, where fans accelerate the rapid deterioration of flux and oxidation of solder particles.

Adjusting the profile to flux, this problem is solved on most machinery by adjusting the speed of the conveyor belt. This reduces the switching time for machines. Soldering using flux that reacts quickly to heat curbs the impact of heat on the parts and board. At the same time, it also solves the problems of voids and spattering. Because excessive heat causes flux to deteriorate, flux deterioration must be prevented in the preheat stage until the solder melts.

Material sources
Kojima Solder
Yuyama Co. Ltd.
Kouei Electric
Nippon Antom Co., Ltd.
Edsyn International Co., Ltd.
Hirox Corporation

Photographic equipment
Digital Microscope
Hirox KH-7700/KH-1 300
http://www.hirox.com