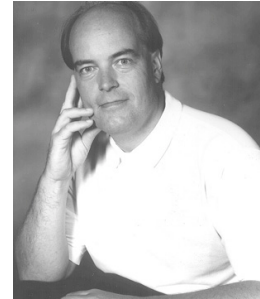


Lead-Free Fillet Lifting - It Happens in Reflow and Wave Soldering

Bob Willis
Electronic Presentation Services
Chelmsford, England



Abstract

Fillet lifting is really the only new process phenomena observed by engineers working on introduction and reliability studies for lead-free. Fillet lifting was first seen in Japan during early product introduction, it was also seen in the European IDEALS Project and research work conducted by GEC back in 1993. It has subsequently been highlighted in reports by NEMI and NIST in the USA, Soldertec and NPL in the UK and other researchers in mainland Europe. To date fillet lifting has not been associated with joint failure on products.

As part of the SMART Group Mission to Japan, at a Briefing in Tokyo at the British Embassy the issue of fillet lift was debated with leading suppliers like Sony, Panasonic, Denso, NEC and Toshiba. During discussions one company suggested that they had experienced a single failure when a track was located at the track/pad interface, when the pad lifted from the surface of the board rather than the fillet from the pad. This failure was the only reported case found during initial process evaluations.

Most engineers associate fillet lifting with the wave soldering process but production trials have also seen it occur with Pin In Hole Intrusive Reflow (PIHIR). It may also occur in selective soldering but to date no practical trials have been conducted with this process and lead-free alloys. Discussions with other engineers working on lead-free have not found the defect with selective soldering, however most had not specifically conducted examination for this fault.

This paper will outline some of the reasons for fillet lifting, the process stages, where it has been seen and the possible impact on solder joint reliability. Process trials with different solder alloys, alternative solder finishes on wave and intrusive reflow will also be outlined.

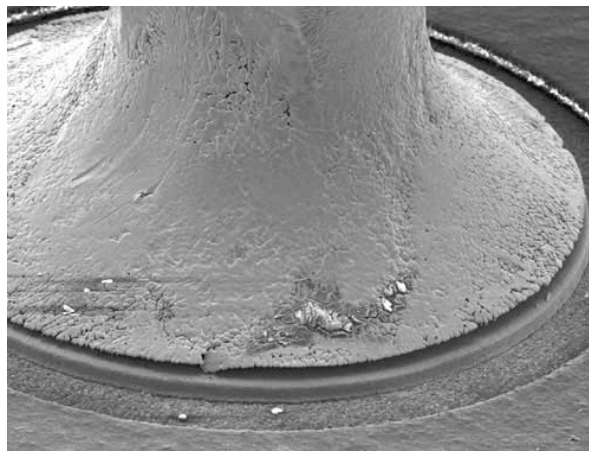
Introduction

There is growing interest in lead-free soldering in Europe and in most parts of the World mainly driven by forthcoming legislation on the use of tin/lead solders. Legislation on the use of lead solders for electronics is set to be banned by July 2006. Many companies in the Far East are currently releasing lead free electronic products and will increase their environmentally friendly drive over the coming months. Increasingly there will be more and more pressure for companies to change prior to 2006, there is evidence that companies are not now accepting products that are not lead-free.

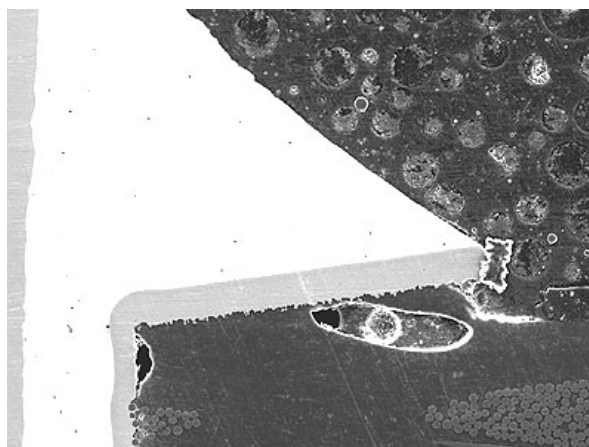
Currently the most favoured alloys to replace tin/lead solders all have a higher reflow temperature than the traditional 63% tin/37% lead eutectic alloy which reflows at approximately 183°C. The favoured materials reflow between 210-227°C which is 30-40°C above conventional tin/lead solders and are tin/silver/copper, tin/copper/nickel and tin/copper. Through hole components were originally designed for wave soldering compatibility, peak temperature on the top side of the board has been limited to between 120-170°C often through hole parts have standoff feet which again limit the peak temperature of the parts. Most surface mount parts that are wave soldered should be able to stand up to a peak temperature of 265°C as they pass through the wave.

In the case of connectors and sockets many are ideally suited to be used for lead-free wave soldering. The body of the parts are made from PCT polymers which will stand up to the proposed changes for wave and can also be used in reflow conditions up to 260°C but in reality for lead-free reflow this would be between 240-245°C.

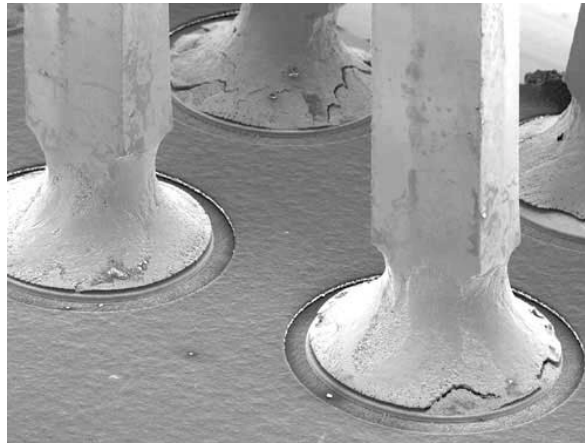
One of the issues originally associated with soldering tin/lead plated parts or printed circuit boards coated with tin/lead deposits is the possibility of fillet lifting. This is where the solder joint lifts off the pad surface. In some case the pad can remain attached to the solder fillet but separate from the PCB laminate as shown in the examples below. Fillet lifting is thought to be caused by differences in solder solidification which are affected by the lead from either the PCB or component lead plating. Lead contamination of the alloy close to the joint interface can lead to a difference in solidification rates in the joint. This issue of lead contamination can also lead to secondary reflow at this point if the assembly is exposed to near reflow conditions. Originally papers suggested this was unique to Bismuth alloys but this does not seem to be the case. To date there have never been product failures reported to be specifically caused by this problem.



Example of fillet lifting on the surface of a printed board using SEM. The solder fillet has partly wetted the surface of the pad but during solidification the edge of the fillet has lifted.



Example of microsection showing pad lifting where the pad is lifted from the surface of the PCB during solidification of the solder joint.



Example of hot tearing which may also be seen on through hole joints with lead-free alloys

Pad lifting is not new to the industry but dates back many years when engineers wave soldered thick multilayer boards with or without through hole parts. In this case the thermal expansion of the PCB may well have been higher than the materials used today. When the board cooled the contraction resulted in pads lifting from the surface of the laminate; much like the example section shown, caused some concerns but did not lead to reported reliability failures. It was not clear at that time if eutectic solder was being used like the conventional 63/37 or the 60/40 tin/lead which does have a small pasty range like many of the new lead-free alloys.

From the trials conducted to date it is clear that each of the fillet problems illustrated can be seen on wave soldering with different lead-free alloys and on reflow of through hole components even with out lead contamination in the joint interfaces. This leads to the possible conclusion that these defects may be more related to thermal expansion and contraction with alloys that have a pasty range.

Over the past couple of years a number of lead-free production lines have been run at exhibitions like Nepcon West, Nepcon Electronics, Productronica and the Hanover Fair. On these lines wave soldering, intrusive reflow and simultaneous double sided reflow process have been demonstrated. The reflow processes have each used tin/silver/copper alloys, in the case of wave soldering tin/silver/copper and tin/copper alloys have been demonstrated. In each case microsections taken by the author show evidence of fillet lifting on through hole joints on topside for wave and on both sides of the PCB when through hole parts are reflowed. It is probably true that if many researchers looked back through their samples and microsections they may see evidence of either of the three process issues previously illustrated.

Visually lead-free solder joints may look slightly different from conventional joints formed with wave soldering or reflowed when compared with traditional tin/lead alloys. This is simply due to the different solder alloy used, solidification rates and the flux which may remain on the surface of the joint during cooling. There is increasing interest in through hole reflow of parts generally referred to as Pin In Hole Intrusive Reflow which can again provide a slightly different appearance. When soldering to a termination there will not necessarily be a continuous unbroken solder fillet between the solder and the pin plating. When the solder paste becomes liquid it will wet the pin and form a reliable intermetallic joint but there will be a difference in the appearance of the joint and the surface of the pin at the joint junction. This is commonly seen on soldering to any non fusible plating like palladium, silver or gold.

Another issue which should be considered generally with lead-free intrusive reflow soldering is the apparent increase in the amount of flux residues on the board after soldering. Due to the higher process temperatures used in reflow; suppliers have adopted higher solids flux vehicles to protect the surface of the metal during reflow. This may add to the residue on the surface of the pins after soldering and may affect the frequency of in circuit test fixture maintenance.

The use of lead-free solder alloys is being driven mainly by political pressure but commercial competition will also have a major impact on our industry. There are technical challenges in the introduction of lead-free alloys but it is an inevitable change which can only be successfully implemented at the design stage of a product.

Lead-free Design in Japan

Products in Japan have always been well designed for the manufacturing process. That has been the case for many years so many of the design tricks to eliminate soldering defects have been implemented. It is fair to say that many of the design tricks to eliminate shorts, solder skips, board bow and traditional processes originated from Japan. Many of the design solutions have been necessary to incorporate into designs due to high volume consumer products produced in this marketplace. Although the Japanese products are traditionally produced for the consumer and telecommunications markets, many of the design for manufacture rules can benefit all electronic products. The use of drainage pads to eliminate solder shorts, narrow pads to eliminate cracking of solder joints and no-go areas on the base of the board to allow centre board support on wave soldering systems are common place on board designs in Japan but less so in Europe and USA.

During the SMART Group Mission to Japan the issue of fillet lifting was discussed. One company had conducted a project which they felt had significantly reduced the problem. Essentially there are no specific design rule or layout changes for lead-free assembly and soldering which have been widely implemented in Japan. Modifications have been made to overcome process defects like fillet failures or to adapt board designs to alternative soldering processes.

The only specific design change introduced to reduce solder fillet failures was a change to the size of the solderable pads on the printed board. This was achieved by using resist-defined pads where the resist was imaged to overlap the pad surface. This is an alternative to just reducing the pad size which should also provide a similar result. On plated through holes the pad size has little impact on joint strength, on single sided boards the pad and hole to lead ratio are key to the joint loading strength.

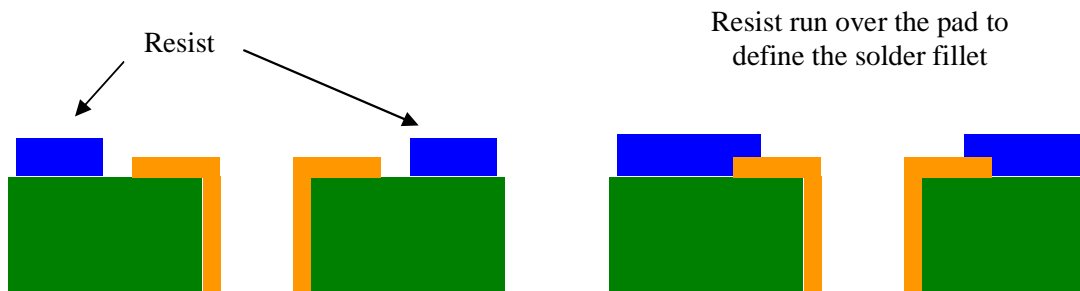
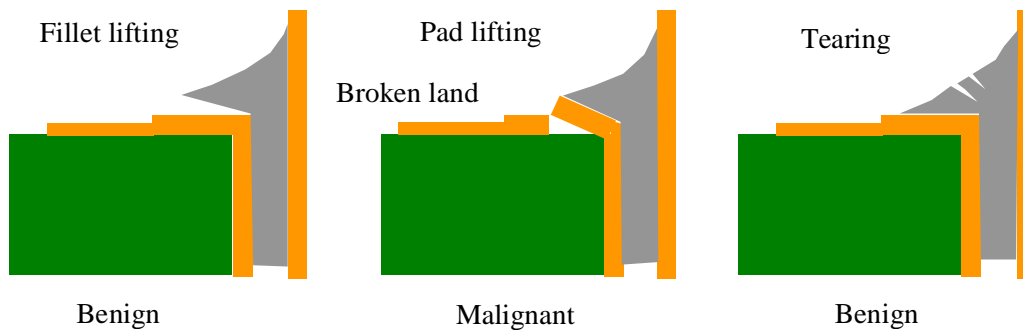


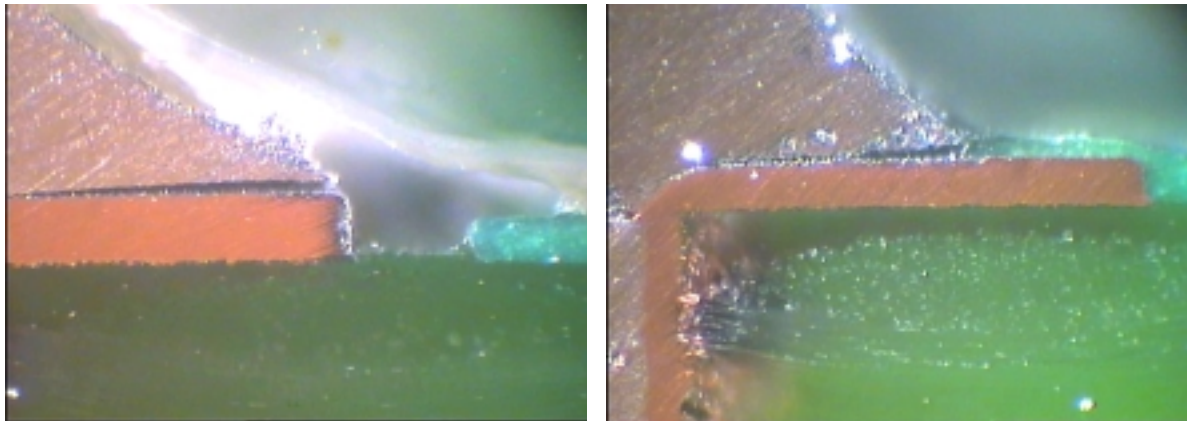
Figure shows cross sectional views of the plated through hole, surface pads and resist aperture both before and after the design rule change.

The illustration shows the change to using the resist aperture to define the pad surface. This technique to reduce the fillet failures was highlighted by Sony, Panasonic and Toshiba during the initial round table discussions at the British Embassy, after the Mission seminar only Sony and NEC highlighted the design change. Examples taken from the SMART Group Mission to Japan Report

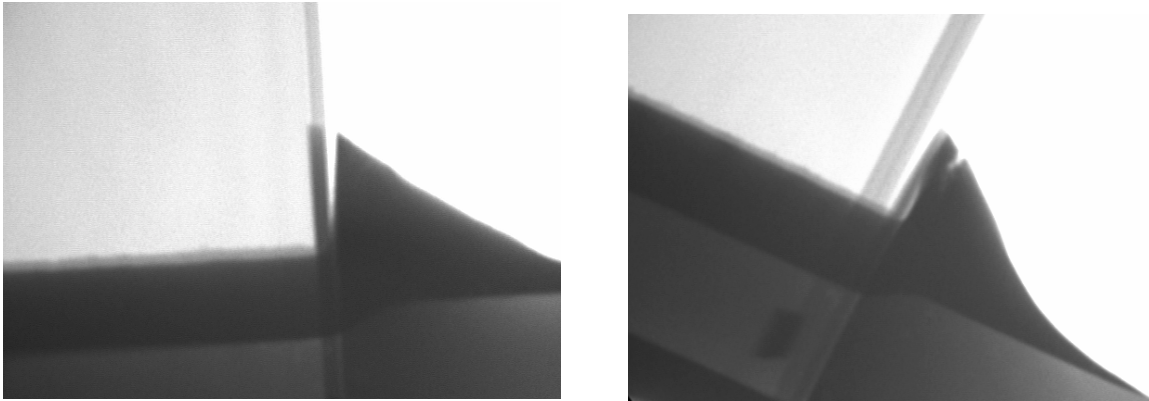
By reducing the pad surface on the topside of the board the fillet extension is reduced, the fillet does not add significantly to the strength of the joint. In the case of traditional design rules it would be common to see solder not fully wetting out across the top pad surface leading to a cosmetic defect or process indicator. By reducing the pad surface it makes full coverage of the reduced pad surface easier to achieve. With limited flow across the pads the lever effect on the corner of the hole would be less and may be the reason why this has provided some positive results. Minor lifting would however be masked by the resist thickness if only visual inspection was conducted. The Japanese companies considered that fillet lifting and fillet tearing were benign; pad lifting was considered to be a potential problem as shown below.



Examples taken from the SMART Group Mission to Japan Report



Microsections from Independent trials by the author on both wave and intrusive reflow have indicated that this design change alone may still provide fillet lifting, it is clearly seen in the example section but more difficult to detect with visual inspection.



Fillet lift and tearing can be detected with X-ray inspection, both examples where produced in reflow

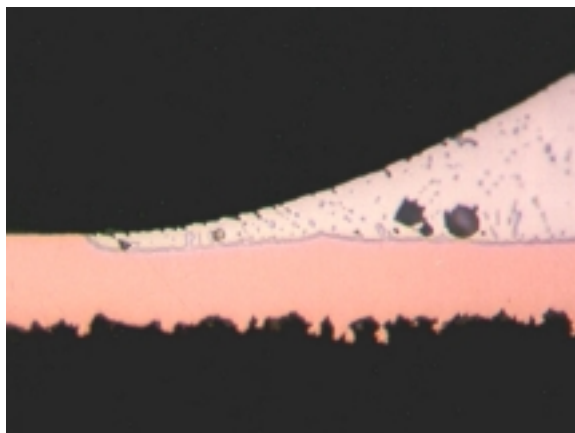
Additional Wave Soldering Trials

As engineers have found there are a number of major wave soldering process issues that need to be considered during process trials:

*Increased solder shorts
Solder fillet lifting/pad lifting/joint tearing
Increased board sagging*

*Wave solder bath/ducting erosion
Better topside temperature control
Potential copper track erosion*

The following trials concentrate on two issues, fillet lifting discussed earlier and copper erosion of surface tracking on the printed board in contact with the wave. To date this issue has had little attention but potentially when looking at the following image some engineers may have concerns. Example microsections have been shown in international seminars and discussed in technical forums which show marked copper reduction, but no details on the process used have been issued.



Example microsection produced as part of the evaluation showing copper erosion on the copper track. (IDEALS Lead Free Project)

When this issue was first discussed with other engineers very few people had observed the phenomena. In fact, a review of all the author's previously produced microsections showed little evidence of the problem. During a review of many of the lead-free sections produced by National Physical Laboratory (NPL) no significant evidence of erosion could be found.

It is fair to say that increased copper dissolution into the solder wave was considered inevitable due to increased wave soldering temperatures and high tin contents in alternative alloys. Concerns were expressed at the impact of high copper levels but this really relates to our experience with tin/lead alloys. Copper is the main contaminant found during normal production; it does impact the soldering yield by increasing solder shorts. Higher copper levels do make a difference to the visual appearance of the joint. However, it has never been shown to impact on joint reliability. With lead-free copper it is already part of the alloy, between 0.5 - 0.7% added to the mix, as it is a cheap filler metal.

To re-examine the possibility of fillet lifting on different processes and for copper erosion during wave soldering a short trial was conducted with three different printed board surface finishes:

- OSP on copper
- Gold over nickel
- Silver

The boards were standard 1.6mm FR4 laminate with plated through hole and photo imagable solder resist. The hole size was 0.9mm after plating, one row of holes was used for assessment with holes linked to exposed tracks. In addition, two parallel tracks exposed for soldering were examined. Half of the track length was covered with Kapton tape to protect the surface from soldering, the aim being to solder part of the tracks. This allowed comparison of the original copper thickness on each board and the remaining copper thickness after soldering.

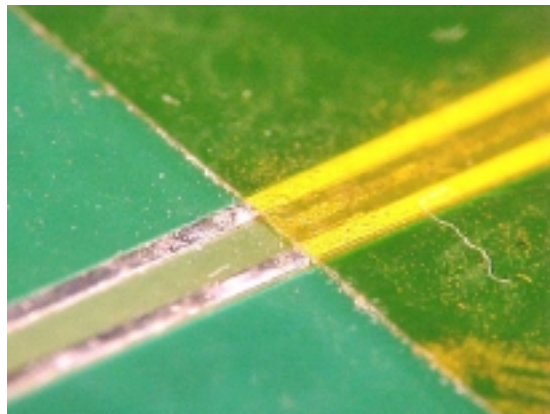


Figure shows one test area with two parallel tracks with Kapton tape applied

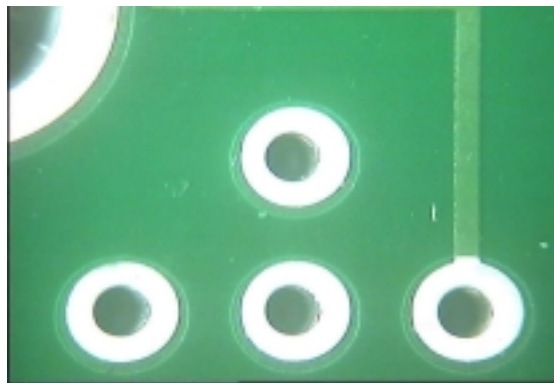


Figure shows through hole with track connection point used for examination.

The through hole component used in the study was a 96-way PCB edge connector supplied by Harting Connectors. The connector pin featured a lead measuring 0.75 x 0.75mm with a tin plated finish. The use of the multi-leaded connector allows the continued investigation of fillet lifting phenomena with copper erosion. A total of six boards were provided for soldering trials, two of each of the different PCB solder finish. The gold boards were included in the trial for completeness, however, the soldering and copper erosion would not be any issue with this finish as the underlayer of nickel would protect the copper. Dissolution of nickel is much slower than copper during soldering. The boards were wave soldered by:

Tin-Technology - Soldertec, England
Electrovert, USA
Nihon Superior, Japan

The solder alloys used in these trials featured

tin/silver/copper	Sn 3.8Ag 0.7 Cu	Multicore
tin/silver/copper	Sn96.5 Ag3.0 Cu0.5	Alpha Metals
tin/copper/nickel	Sn 0.7Cu Ni	Nihon Superior Co Ltd
tin/copper	Sn97.3 Cu0.7	

The parameters used in the trials were approximately the same. Ideally, for a trial of this type, a common set of parameters is used with one machine. However, engineers now understand trying to run trials and change alloys in one machine is not a simple or inexpensive task. The three companies were kind enough to process the sample boards and return them for examination. The tin/copper samples were processed as part of a previous trial but on the same sample board design.

England

Flux	Multicore X33-081
Conveyor speed	1m/min
Wave temperature	260°C
Pre-heat	120°C topside
Contact time	4 sec approximately
Machine	Seho

Japan

Flux	Tamura EC 19S8
Conveyor speed	1m/min
Wave temperature	255°C
Pre-heat	130°C PTH board temperature
Conveyor Angle	4.75°
Contact time	4.5 sec approximately
Machine	Electrovert

USA

Flux	Alpha 330
Conveyor speed	1.2m/min
Wave temperature	260°C
Pre-heat Vectra Heat	120 & 150°C
Contact time	5 sec approximately
Machine	Electrovert



Figure shows one termination point with track connection to the pad after soldering, this connection point was examined on all boards on the top and bottom side of the boards for any evidence of pad lift and track separation similar to the example reported in Japan. None were found.

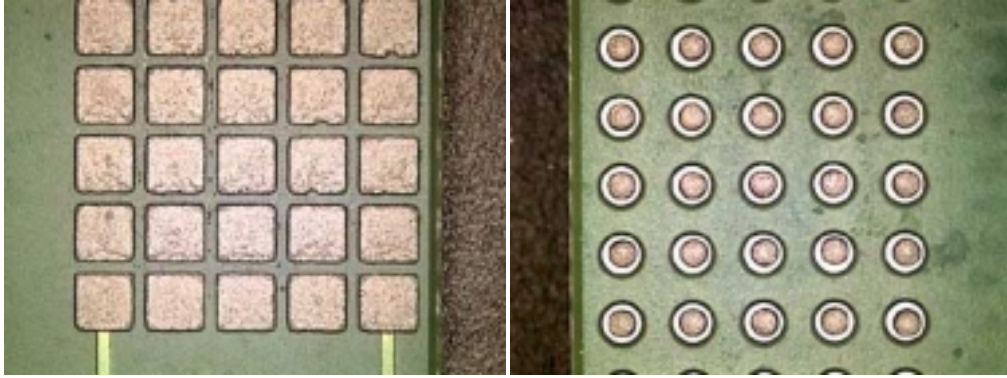
The quality of the soldering with each of the sample batches was similar with some evidence of bulbous joints and shorts. The boards produced in the USA featured poor through hole fill which was most likely related to the flux penetration into the through holes. The soldering quality of the bottom side of the board and the wetting to the through hole and lead section was satisfactory. The solderability was not in question as all the boards were from the same batches which were processed in Japan and England.

Microsection examination showed evidence of the same three fillet issues seen during visual inspection, the fillet phenomena was evident on all samples. The general soldering quality to the plated through hole and pins were all found to be satisfactory. There was little evidence of the copper erosion on any of the samples other than would be expected with normal intermetallic formation of 2-3um, slightly more than may be seen with traditional tin/lead alloys.

Pin In Hole Reflow Trials

The basic PIHR process starts with stencil printing the surface of the board with solder paste. Traditionally stencil printing is conducted for surface mount terminations but with PIHR solder paste it is also printed over the through hole pads and into the holes. On the production trial tin/silver/copper alloy was used printed through a 0.006" 150um stencil. The paste flux system has also been designed to work with other alternative alloys like tin/silver, tin/silver/bismuth and tin/silver/bismuth/copper.

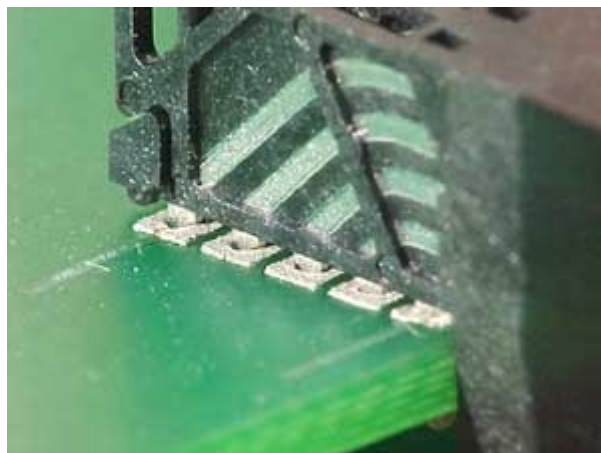
The paste volume printed on the surface of the board is determined by the pitch of the connectors and the standoff features of the connector body. The selection of the stencil thickness was also determined by other fine pitch parts on the board. Good design of the connectors allows the paste volume to be maximised on the surface of the pads and onto the surface of the solder mask.



The print deposits produced maximized the surface area on the topside of the board as well as through the holes as shown on the two examples above

The printing process used featured a Rheometric sealed print head which has the benefit of increasing the penetration capability of the paste into the hole as well as minimising the waste associated with traditional blade printing processes. The print penetration into the holes in the example photograph shows better than 80% fill. Standard blade printing can be used for through hole parts with a thicker stencil but a sealed head can markedly improve the hole filling capability.

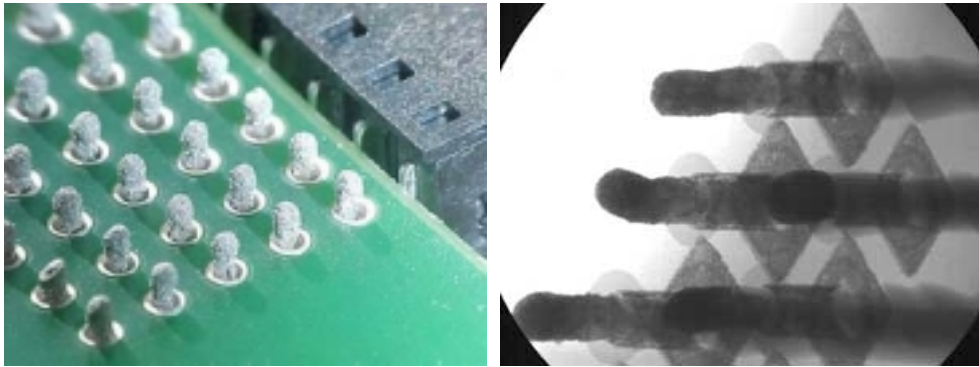
After printing, surface mount components may be placed on the surface of the paste prior to insertion of the connectors into the pasted through holes; depending on the design the connectors may be inserted first. It has often been difficult for engineers to automate the odd form assembly process due to the need to invest in additional odd form equipment. Now with selected placement machines having the capability to insert all the popular surface mount shapes and odd form parts it opens up the opportunity for greater use of PIHR technology. The printed board design featured three connectors, 0201 and 0402 chip components as well as BGA, Flip Chip and QFP parts soldered on silver, copper OSP and gold PCB finishes.



The 110 pin row connector especially designed to minimise temperature differentials on the surface of the board during reflow and remain designed for automatic assembly

A 96-way right angled connector, 16 pin post header and 110 pin connector were all assembled using a universal head. Vision checks were made on each part to accurately align the through hole leads with the plated through hole. It should be noted that accurate insertion requires vision systems to have the capability to check through hole position accuracy as well as the traditional fiducial marks associated with surface mount technology. It is well understood that drilling and photo imaging of printed boards can have a large tolerance, the base PCB materials can change their dimensions by 0.001" per inch.

Ideally all components are provided in tape and reel formats for production but on long parts like the 96 way they can take up valuable feeder space so versatility is also important on packaging selection for odd form parts. While running the trials three formats of packaging were used. Placement was from tape and reel, stick feed for the IDC post headers and machined plates for the 96-way edge connectors. As the plates were being used in an automatic tray feeder, part positions were also provided for the other two connector designs to give added flexibility.



Two examples of the 110 pin connector after assembly and prior to reflow soldering. The first view shows the base of the board after insertion of the connector and limited paste displacement on the tips of the pins. The second view, and slightly more unusual, is the X-ray image of the board with the paste deposit visible on both sides of the board prior to reflow

When automatic assembly was complete the board was conveyed to the reflow process to simultaneously reflow the surface mount and the through hole joints in one operation. The reflow system featured pin transfer conveyor to avoid contact with the pasted pins which protrude below the board surface. The size of the oven in terms of length and number of zones will normally be dependent on the throughput speed required. Basically an oven is selected for its throughput requirements and its compatibility of the product type and the peak temperatures required. The most popular lead-free solder pastes can be processed at 240°C or below. It is important to correctly profile the board assembly as the connector may be the largest component on the surface of the board in terms of mass so the through hole parts should be one of the areas selected to monitor and check the differential temperature on the surface of the board.

The test board consisted of a wide selection of surface mount components as well as the connector. To date the samples have been through thermal cycle testing of 2200 cycles of -55oC +125oC with dwell times of 40 mins. with no electrical failure.

A further feature of the NPL pin in hole reliability project involved the use of different stencil apertures in the printing process to obtain a range of solder joint volumes. As the optimum stencil/hole size/pin combination had been provided for the connector pins by Harting Connectors, it was necessary to both increase and decreases the final joint volumes which may be seen in normal manufacturing processes. As none of these through hole reflow joints failed during testing but did feature fillet lifting it is assumed that wave solder joints with the same features would also be satisfactory after being subjected to the same testing.

Fillet lifting can be seen on lead-free solder joints on both wave and reflow. It can be seen on different alloys and on joints where there is no evidence of lead on the PCB or component terminations. Further work to look at the cooling rates after wave and reflow soldering may be a possibility in the future.

Bob Willis is a process engineer consultant working in the industry, providing training and process support, he is also Technical Director of the SMART Group, Europe's largest surface mount trade association. Bob produced the first interactive "Lead Free Assembly & Soldering Cook Book 3" CD-ROM with the National Physics Laboratory and works on other projects at NPL. He has run many lead-free workshops for APEX and IPC as well as hands-on lead-free events for companies worldwide. He can be contacted by email at bob@bobwillis.co.uk or visit the web site www.bobwillis.co.uk