Effect of Contact Time on Lead-Free Wave Soldering

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Abstract
The increasing use of lead-free solder has introduced a new set of process parameters when setting up wave solder equipment for effective soldering. Determining the proper flow characteristics of the solder wave for adequate hole fill is an essential step in achieving a reliable process. A variety of solder waves exist in the industry; each with advantages and disadvantages when performing lead-free wave soldering. One way to ensure adequate hole-fill is by increasing contact time at the Chip Wave.

This paper will present recent work done on an innovative way of increasing contact time, hence improving hole fill for relatively challenging board design. This work also examines effect of various process parameters including effect of nitrogen on hole fill. In addition to the experimental work, comparison and discussion of many variations of solder waves including: "A" type waves, laminar waves, dual waves, inerted shrouds, tunnels, and non-inerted waves will be discussed in this paper. Information will be provided on improved utilization of old wave solder equipment and the correct selections of new equipment to optimize lead-free wave soldering.

Introduction
The transition to lead-free wave soldering continues at many sites. As end products become more "green", process engineers face more complex assemblies requiring the use of lead-free solder. If we think about an SMT assembly line in terms of what is actually manufactured, it leads us to that shown in Figure 1, the solder joint. Board laminates; components, connectors, etc. are, in general, manufactured elsewhere. This is surprising to some yet when we think about SMT assembly in regards to what is actually manufactured, it leads to the solder joint. Most board assembly companies spend millions of dollars on inspection equipment, placement machines, printing machines, and line monitoring yet invest the minimum possible into the machines that perform the only item that is truly manufactured.

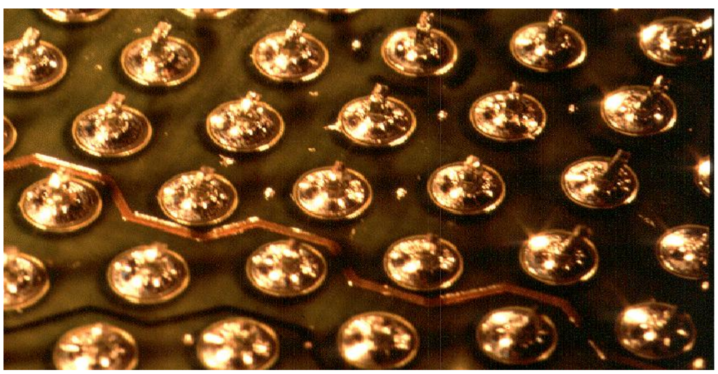

Figure 1 – Solder Joints

In addition to the complexities of the lead-free wave soldering process, board complexity overall is increasing. Large multi-layer server boards are increasing the demands upon the wave solder process whether it be lead-free or lead based soldering. Though not produced in large volumes the dollar value and profitability of these high end board assemblies drives the need for high first pass yield and minimal rework. When soldered on conventional wave soldering technology these boards are characterized by low yield, slow production speeds, and rework which increases the latent failure risk. The main process problem experienced is hole fill. Thick substrates, heavy ground planes, and large components rob the heat necessary for a solder joint to properly form. Long contact solder nozzles now exist that can improve the yield, increase the soldering speed, and improve the hole fill for successful soldering of these complex assemblies.

Solder Nozzle Variations
Wave soldering machine manufacturers provide many nozzle variations and configurations with a plethora of gadgetry and widgets within or surrounding the solder wave all with claims of unsurpassed soldering performance. With the assumption that our substrates and components are not defective, what is required for good solder joints is; plenty of

heat, contact time, adequate flux, solderable surfaces, and good flow characteristics when the circuit board exits/peels away from the wave. When troubleshooting wave solder process problems, keeping these basic requirements in mind can go a long way in solving the problem quickly. Nifty nozzle widgets will not yield acceptable soldering if the basic soldering requirements are not up to par.

In the simplest of categorizations, wave soldering is done with either a single wave or a dual wave process. Single wave systems consist of some type of a laminar flow smooth wave. Dual wave systems have an additional wave preceding the smooth wave that is turbulent in nature. Of the smooth wave systems there are two basic types. The first type is known as an "A" wave and has a bi-directional flow with high velocity on both sides of the wave. The second type is characterized by a high velocity flow on the leading side of the wave with a slower flow, matched to the conveyor speed, on the trailing side of the nozzle known as the Laminar or Lambda type wave. Turbulent waves, used in dual wave systems, are generally narrow in width and are …. "TURBULENT". These provide additional contact time, reduce the shadowing effect of components, and make extra dross. With the escalating price of lead-free solder, if it's not needed, don't use it. Figure 2 below illustrates the basic waveforms provided by wave solder manufacturers.

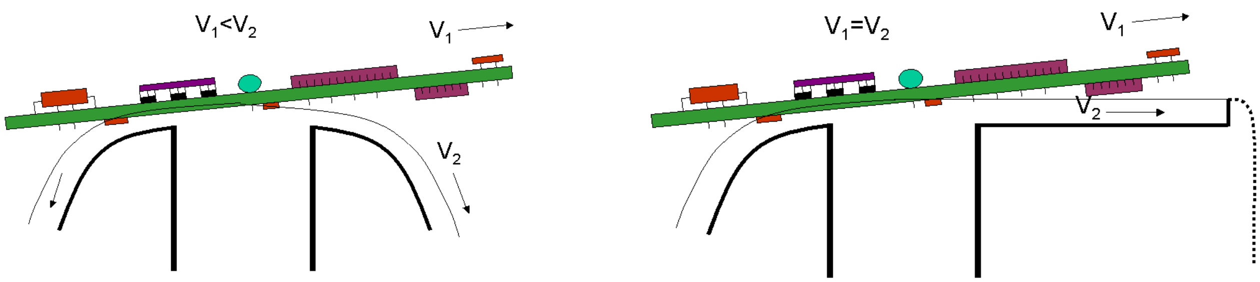

Figure 2 – Basic Wave Solder Nozzle Profiles

Recent developments have provided for an extended contact dual wave system known as the Dwell Max[1], whereby a wide turbulent wave is combined with an extended contact smooth wave. This set-up is becoming popular for the highly complex, thick substrate, palletized server boards and illustrated below in Figure 3.

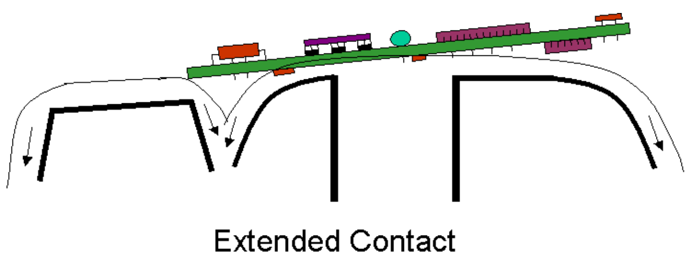

Figure 3 – Dwell Max Wave System

Each nozzle type and configuration will have characteristic solder contact/dwell times at a particular conveyor speed. Generally, single wave A-type nozzles will have the shortest times with the dual wave extended contact systems having the longest. Table 1 below gives contact times for the various common types of nozzle configurations.

Table 1 – Contact Time

Nozzle Type	**Conveyor Speed**	
	0.8 m/min	**1.4 m/min**
Single A-Type	3.6 seconds	2.0 seconds
Single Smooth	4.9 seconds	2.8 seconds
Dual wave A-type	4.3 seconds	2.4 seconds
Dual wave Smooth	5.7 seconds	3.2 seconds
Dual Extended Contact	10.5 seconds	6.0 seconds

Wave Soldering Atmosphere

Along with the various nozzle configurations that are available, we have the choice to solder in the air atmosphere provided by Mother Nature, or an inert nitrogen environment. Again all sorts of gizmos and gadgets exist to provide for the "best" inert atmosphere for soldering but the choices boil down to two types of systems, boundary layer and tunnel.

Tunnel systems provide an enclosure surrounding the wave solder area of the machine and completely inert the product and solder bath as the substrate passes through. Early tunnel systems inert the entire process including the preheat sections. Experience shows that the extra nitrogen consumption and maintenance required for these type systems are excessive. Over time, tunnels that inert in the wave area only have become the preferred system when inerting is required. Boundary layer systems inert the lower side of the circuit board only and utilize the circuit board itself to provide for the inert atmosphere. Tunnel systems create much less dross, provide for shiny top side solder fillets, and are more expensive to operate in terms of maintenance, nitrogen consumption, and capital expenditure. Boundary layer systems create a bit more dross, less equipment costs, and only inert the area where the action is taking place with the solder wave.

Nozzle Selection

With all of the options available which is the best for the lead-free applications? Unfortunately, there is no one system that will satisfy all. Each process owner must review the products that are to be manufactured on an assembly line and choose the type of system that will serve their needs the best. "A" type waves, with their short contact times, may be completely adequate to solder simple thin lead-free circuit boards but will cause difficulty when soldering products with any complexity or thickness. Extended contact waves may be great for large server boards soldered with lead-free but may de-laminate a thin, lead-free, consumer type product. Good up front board design and process development with the machine manufacturer is strongly recommended before choosing any equipment configuration. Table 2 below categorizes basic board complexities and can serve as a rule of thumb for wave solder nozzle selection.

Table 2 – Board Complexity

Cat.	Characteristics	Process Factors	Nozzle Types
1	-0.062" thick or less -Low thermal challenge -Low population density -Size under 10" x 12"	-Preheat is flexible -Contact time < 5 seconds -Pot temperature 250C to 265C -Simple tooling, if any -Rework is less challenging	-Single A-Wave -Single Smooth wave -Dual wave if needed
2	-0.093" thickness -Thermal challenges increase -Population density will vary -Sizes vary, but often as above	-Process window narrows on all fronts -Contact time often 5 - 7 seconds -Pot temperature increases to 265C + -Rework difficult but achievable	-Smooth wave with turbulent -Extended contact dual wave
3	-Over 0.093 in thickness up to 3/16" -Significant thermal and design issues -Boards are large and of high value -Sensitive mixed technology design	-Large, thick and heavy selective solder pallets are common -Contact time over 7 seconds -Rework can easily result in scrap -The influence of process on long term reliability becomes a factor	-Extended contact dual wave

Given the focus of this paper, the continued discussion will center on the multi-layer type 3 thick server board and solving the hole fill difficulties when soldering in lead-free.

Hole Fill >0.093" Boards

Prior to the development of the extended contact dual wave system, process engineers were limited to slowing the conveyor speed to increase contact time and achieve better yield. Unfortunately, this decreases productivity and increases thermal degradation of the product. To compound the problem, slower speeds in the A-type and smooth wave nozzle systems allow for an increased drop in temperature between the last preheater and the first wave as well as between the two waves in a dual wave system. These drops in temperatures must be made up and therefore drove even slower speeds as the entry contact lengths of the solder waves would be reheating the joints and lost for the process. Additionally, solidification of the solder joint between waves causes increased degradation of the remaining flux that is above the partially filled solder joint.

The solution was to provide for more contact and to minimize the drop in temperature as the circuit board passes between the two waves. This was solved by significantly increasing the width of the initial turbulent wave and by minimizing the gap between the turbulent wave and the smooth wave. Increasing the width of the turbulent portion of the solder wave increases heat transfer over a similar length smooth wave. The turbulence and activity of this wave provides a higher conductive heat transfer to the solder joint. These improvements have been very beneficial in achieving higher yield and increased productions. Figure 4 illustrates the solder joint thermal profiles that can be expected for the A-type, smooth, and extended contact dual wave systems.

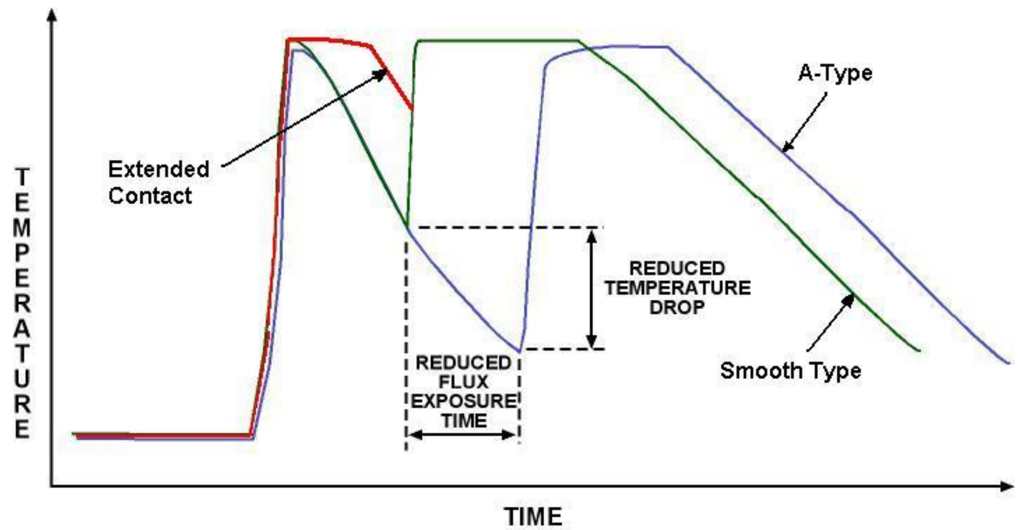

Figure 4 – Solder Joint Thermal Profiles

Process Testing

DOE testing was conducted comparing the extended contact dual wave system with the dual smooth wave system. Hole fill, shorts, and excess solder (lumps) were recorded for QFP's, through hole components, and ground pins. The test board used was a .093" thick board with inner layers of 2oz. Cu. Coating was OSP and one flux was used for all testing as well as one solder alloy (SAC 305). Initial screening tests were completed to determine the low-end deposit rates for the flux that was then used in all testing. Tests were conducted in both air and in a nitrogen tunnel and tests were conducted with conveyor speeds set to provide for both a 3 second and 6 second contact time on the smooth wave. The test vehicle used is shown in Figure 5.

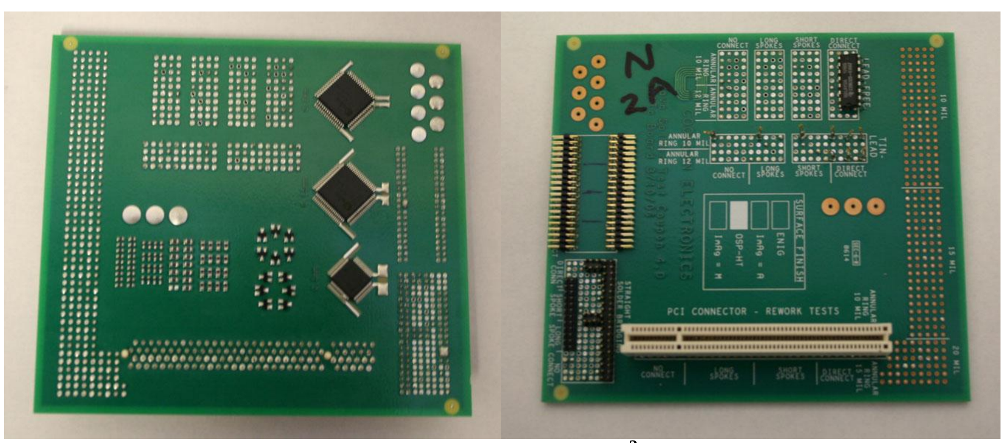

Figure 5 – Test Vehicle[2]

At the conclusion of testing and statistical analysis of the data the extended contact system performed overall superior to the smooth wave system in both nitrogen and air. Figures 6-7 show key gross results. In reference to the figures, the DOE groups are as follows;

1. - Extended contact dual wave in air
2. - Dual Smooth wave in air
3. - Dual Smooth wave in nitrogen
4. - Extended contact dual wave in nitrogen.

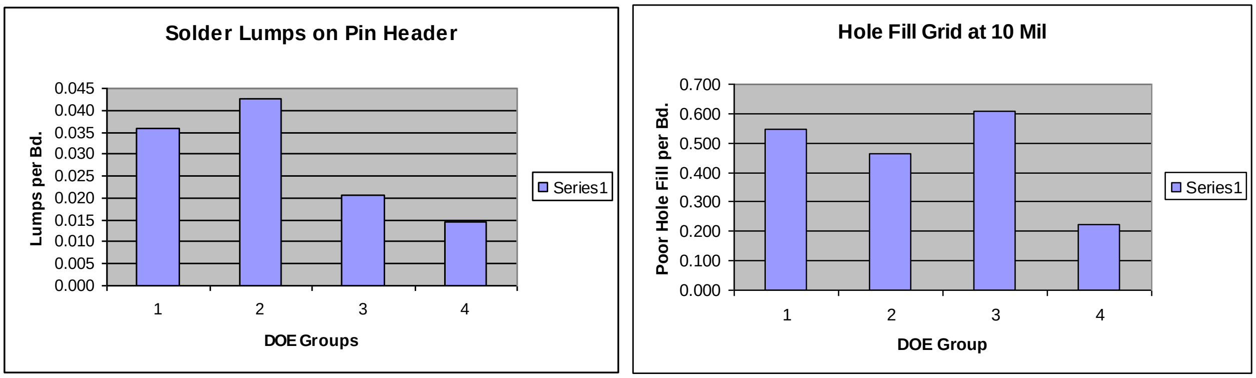

Figure 6 Gross Test Results

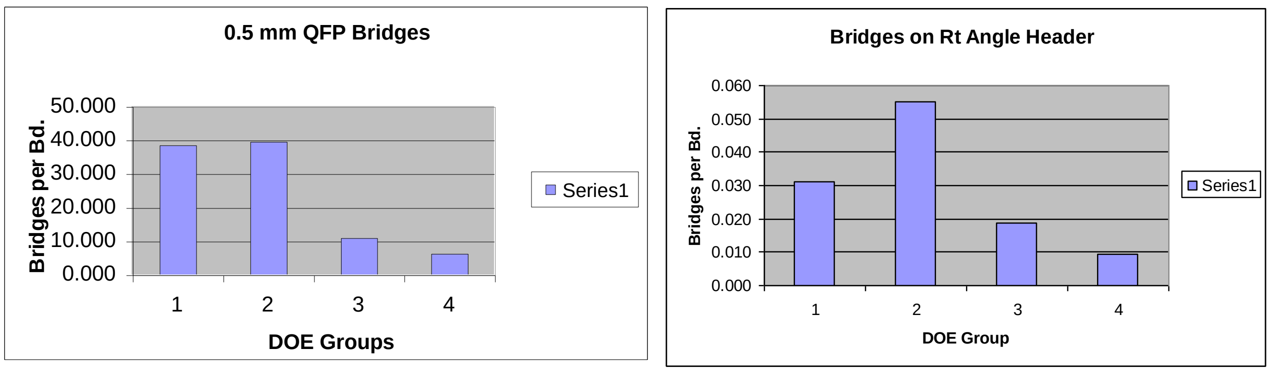

Figure 7 – Gross Test Results

Contact Time vs. Copper Loss

A concern of increasing the contact time is the possibility of degradation of the copper pads and plated through holes (PTH) due to the dissolution and erosion effects of solder, especially the high tin content lead-free. An additional DOE test was conducted to analyze this effect. Four factors were established for the DOE: Alloy type, conveyor speed, wave form, and board vendors. Board vendor was used as a variable to reduce the sway of data otherwise possible if you used only one board, from one vendor, with one date code. Using 2 vendors and 2 boards can confirm that results can translate to a variety of pieces. Response factor was the thickness of Cu from the solder filled plated through hole. PTH sections were taken and Cu thickness measured and compared between virgin epoxy filled and solder filled PTH's. Alloys used were SAC305 and Proprietary tin-copper-nickel alloy lead-free solders. Conveyor speeds used were 1.5, 3.0, and 4.5 ft/min and two board vendors provided substrates. A total of 36 runs were completed. Figure 8 below illustrates the method used for determining the before and after thickness changes.

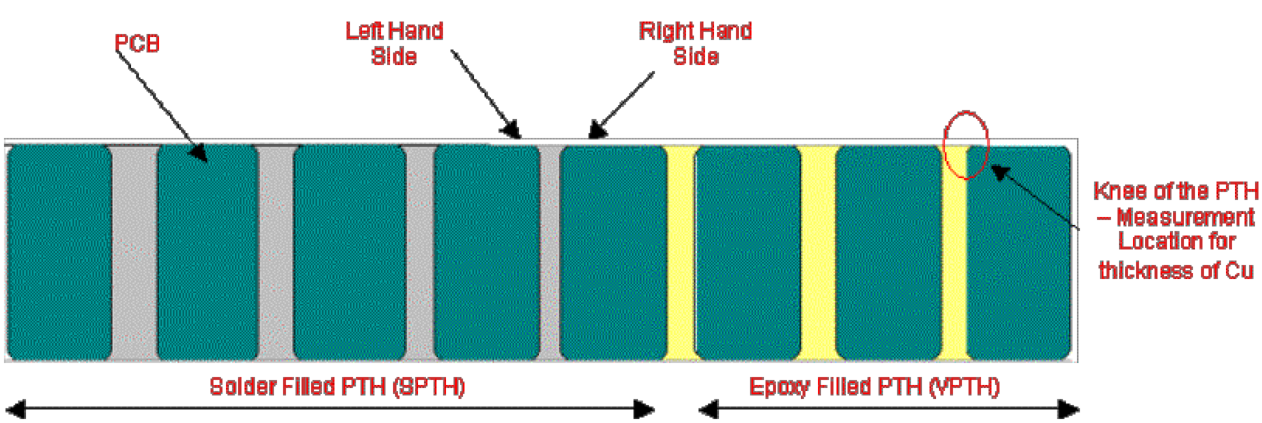

Figure 8 – Test Method Illustration

It should be noted that variation in Cu within a board was pronounced and reached as high as 50 microns, however, this variability was factored in when comparing the before and after effects. Figure 9 below shows a typical cross section of one of the test samples.

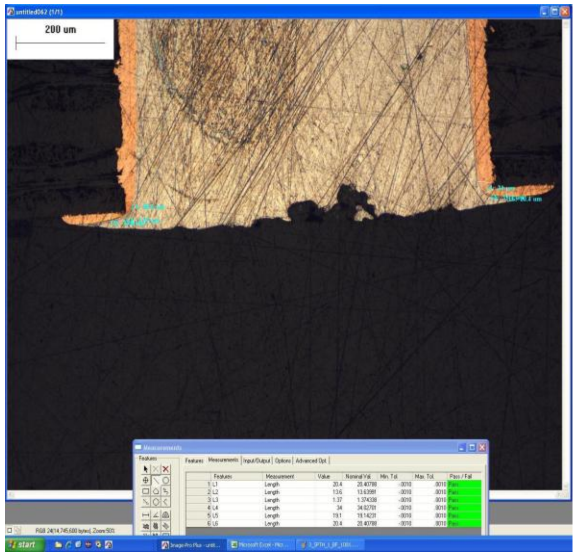

Figure 9 - **SPTH (Wave Form – Chip+Main, SAC 305, Conveyor Speed-1.5FPM, Board Vendor - A)**

Of the four factors considered the wave form had the largest effect on Cu erosion. The three wave forms tested were; single wide turbulent wave, single smooth wave, and dual waves with both on. Figure 10 shows the measured Cu loss between the two alloy types tested at the three conveyor speeds.

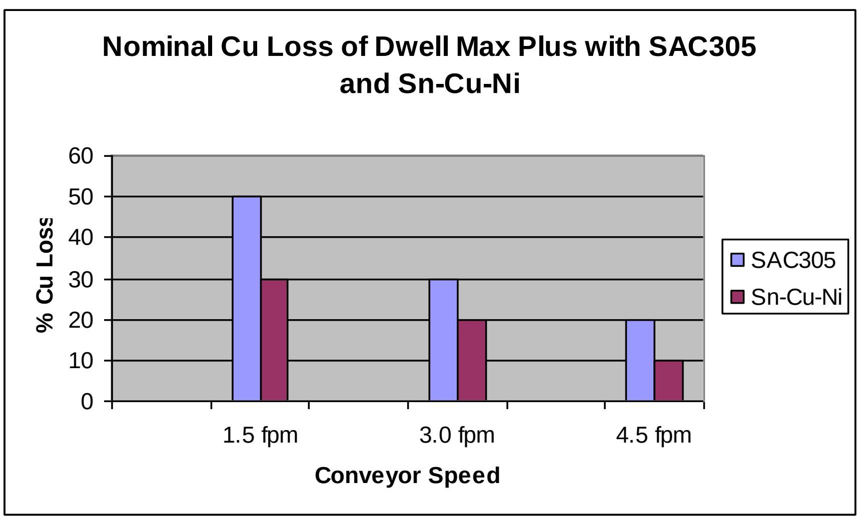

Figure 10 – Copper Loss at Conveyor Speeds

Overall conclusions drawn from this testing were:

1. Copper is removed due to contact time.
2. The Sn-Cu-Ni alloy, as predicted by other work, did remove less material.
3. There was not as strong an indication that erosion was more significant than dissolution.
4. The finding of board and the board vendor variation is significant not only because of the range from hole to hole, but because it should drive a whole different approach to future claims of copper loss strictly due to the alloys used.
5. Long contact solder processes in any alloy will bear influence on knee dimension, and consequently are a consideration in process design. Unfortunately, the quantitative data needed to make a sound process decision upon require micro-section analysis, and, the variation in the single board, and between boards, much less between different lots and different board vendors is a complete uncontrolled variable at this time.

Field Experience

Feedback from users utilizing the extended contact dual wave within a tunnel has been positive. At one site, defects were reduced by 47% improving the defect rates from 47dpm to 25dpm. This product was a large thick server type board. Hole fill was improved and solder voids eliminated. Additionally, dross was reduced from1.4 Kg/hr. to 30 grams/hour increasing the de-dross maintenance interval from every 8 hours to 72 hours. Figure 11 shows a visual comparison of the dross produced between a system running in air (right), boundary type system (middle), and a tunnel system (left).

Figure 11 – Dross Comparison

Conclusions

Many variations exist between wave solder nozzle designs, each providing different advantages and disadvantages. Differences in wave contact time between these systems are varied and are key factors in providing good quality solder joints. Process engineers should consider the product being soldered and select the nozzle system best suited. Lead-free solder continues to create new process challenges in wave soldering. Thick complex circuit boards with heavy ground planes create very difficult soldering when soldered on standard type nozzles currently available. Utilization of extended contact type nozzles will overcome these difficulties and provide improved yield, less operating costs, and more reliable products. Copper dissolution and erosion can be a problem on any solder nozzle where extended contact occurs. It is important that this is understood prior to setting up a process. Work done at numerous locations has proven that some L-F alloys, given long contact times, can completely dissolve an annular ring. Copper dissolution may also occur on inner layers, compounding an in-service reliability concern. Board designers should consider this when designing thick circuit boards that require long contact times. Extended contact soldering, in combination with a full inert tunnel, can provide an extremely flexible and low cost of method of soldering for lead-free applications as well as traditional Sn/Pb soldering.

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References

1. Dwell Max – Trademark property of Speedline Technologies.
2. Cookson SKATe 4.0 test vehicle.