Productivity and Cost Efficiency of Lead-Free Selective Soldering

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Introduction

With the advent of widespread lead-free soldering, the issue of copper erosion has surfaced as a major quality concern when soldering RoHS compliant through-hole devices. Many contract electronic manufacturers and original equipment manufacturers who have implemented lead-free soldering in production volumes have experienced the phenomenon of copper dissolution. The ability to control this issue is paramount to assuring long-term product quality.

Many circuit board designs are predominately SMT while also containing interconnection hardware, displays and other through-hole components. This variation in thermal component mass often requires elongated solder dwell times which exacerbates the effects of copper erosion immediately adjacent to through-hole solder pads and plated thru-hole barrels.

Lead-free wave soldering of through-hole devices often results in a greater occurrence of first-pass solder defects due to the differences in wetting and flow characteristics of lead-free versus conventional tin-lead solder alloys. This generally results in a greater propensity of post-wave soldering rework and repair often performed with a static solder pot or fountain-based soldering system with limited control over critical process parameters other than solder pot temperature, contact time and solder flow rate.

Mini-wave selective soldering systems employing advanced solder delivery technology, solder nozzles designed for optimized solder flow, and variable tilt angle extraction, provide an alternative for optimal solder joint formation while minimizing copper erosion and solder bridging for a range of printed circuit board interconnection applications.

This paper addresses mini-wave application considerations such as component layout and the resulting effects on solder nozzle design as well as other design for manufacturability considerations. The proper selection of solder nozzles and process parameters, together with several case studies, will be reviewed to assure optimum solderability critical for lead-free soldering applications. Proper understanding of system aspects including flux deposition, preheating techniques, solder application and nozzle design are addressed to insure complete knowledge of the selective soldering process and successful mini-wave applications.

Copper Dissolution

The phenomenon of copper dissolution with lead-free soldering is a major quality concern that is under investigation in several ongoing studies in North America and Europe. The erosion of copper from the printed circuit board was present to a much lesser degree with conventional tin-lead solder since lead within the eutectic alloy functioned as an inhibitor. There is a much greater tendency for copper erosion with lead-free alloys since these alloys dissolve as much as two to four times the amount of copper as tin-lead solder. The reason comes down to the elongated time and temperature process window that is required for lead-free solder alloys because of the difference in their wetting and flow characteristics.

Wetting is an essential prerequisite for soldering of through-hole components, either with conventional wave soldering or selective soldering and means that an interaction has to take place between the molten solder and the component and board surfaces to be soldered. The differences in the wetting properties and flow characteristics between lead-free solder alloys and tin-lead solder have been confirmed with wetting balance testing used to determine the solderability of these alloys. This testing has verified that the majority of lead-free solder alloys exhibit slower zero force wetting time requiring the application of a higher temperature-time boundary and longer dwell time for immersion in the molten solder.

Variations in the thermal mass of through-hole components also requires elongated solder dwell time with lead-free soldering due to the previously referenced sluggish wetting of most lead-free alloys. While elongating the contact time results in improved solderability of lead-free alloys, it significantly increases the effects of copper erosion. These effects are evident with lead-free wave soldering and are pronounced during the rework process which is often performed with a conventional solder fountain. The presence of copper erosion is evident along the entire copper surface but is most prevalent immediately adjacent to the knee of the through-hole solder pad and plated through-hole barrel as can be seen in Figure 1 below[1].

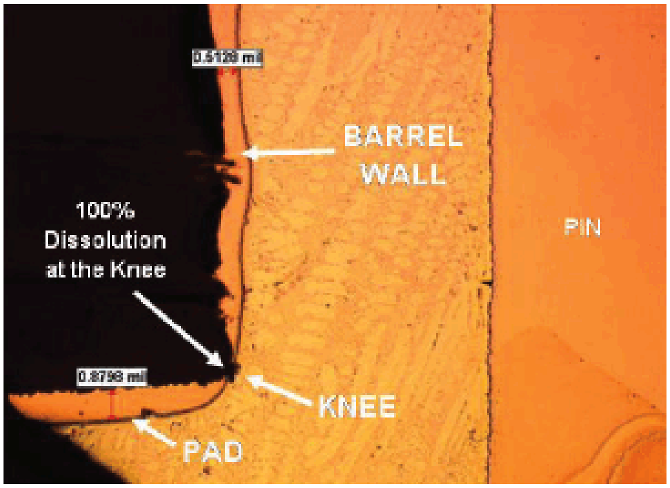

Figure 1 – Cross Section of Plated Through-Hole Barrel

Excessive copper erosion is caused by tin-copper reaction forming intermetallic compounds that flake off from the plated surfaces of the printed circuit board due to the agitation of the molten solder flow which can potentially lead to quality and reliability issues. While there has been limited research on the long-term reliability effects of copper dissolution including reliability tests such as temperature and humidity cycling, as well as shock and vibration testing, there is a concern that failures could persist with prolonged thermal cycling. Finite element modeling of the boundary condition after rework indicates a stress location from a crack in the copper plating at the barrel knee[2]. The failure modes that have been observed include exposed copper surface traces or damage around the knee of the plated through-hole barrel. Although few electrical opens have been observed, long-term product reliability remains an issue as cracks in the surface trace and barrel knee could potentially propagate during prolonged temperature cycling throughout the life cycle of an end product.

There are noticeable differences in the rate of copper dissolution for lead-free solder alloys. Tin-silver-copper (Sn-Ag-Cu) has an average rate of copper dissolution of 0.020 mils/second of contact time, which is double the rate of tin-copper-nickel (Sn-Cu-Ni) at 0.010 mils/second of contact time which in turn is significantly greater than 0.005 mils/second exhibited by tin-lead (Sn-Pb) solder. In addition to these different rates of copper dissolution, Sn-Ag-Cu is more prone to voiding within plated through-hole barrels than Sn-Cu-Ni and Sn-Pb alloys. While Sn-Cu-Ni wets slightly slower than Sn-Ag-Cu, the Sn-Cu-Ni alloy is less prone to bridging than Sn-Ag-Cu alloy[3].

Copper dissolution of all lead-free solder alloys is impacted by contact time, solder turbulence, preheat temperature and solder pot temperature. Because the rate of copper dissolution varies by lead-free alloy, a different process window is recommended for each solder alloy. However, it is recommended that the maximum cumulative contact time of all through-hole processing, including wave soldering and post-wave rework should not exceed 45 seconds making a two-time rework effectively impossible to perform without damaging the printed circuit board assembly beyond repair.

Traditional Rework and Repair

While the reduction in copper thickness of plated through-holes increases with cumulative processing through both the lead-free wave soldering and post-wave rework processes, the overall reduction is more acute during the rework process which can consume as much as 0.8 mils, or one-half of the average thickness of copper. In addition to copper erosion being more severe during lead-free rework, there are indications that thick boards of 0.093" and above pose a greater risk because longer contact time with the molten lead-free solder are required due to their higher thermal mass.

Post-wave rework is generally performed with either a static solder pot or fountain-based solder system. These systems have limited control over critical process parameters other than basic control of solder pot temperature, contact time and the rate of flow of molten solder which are usually left up to the operator. The tin-copper reaction that causes copper erosion however is sensitive to temperature, time and the flow dynamics of the molten solder. The design of a manifold type solder nozzle, or solder flow well, that are commonly used in fountain-based systems generate an agitation of the molten solder within the flow well from the center outward. This results in a dynamic scrubbing action which in turn exacerbates copper erosion.

This phenomenon has been documented by observing a greater amount of copper erosion in the center through-hole pins of a multi-pin connector which directly corresponds to the opening within the manifold-type solder nozzle. The effects of this type of flow well design and its aggressive solder flow upon copper erosion as can be seen in Figure 2 below[4].

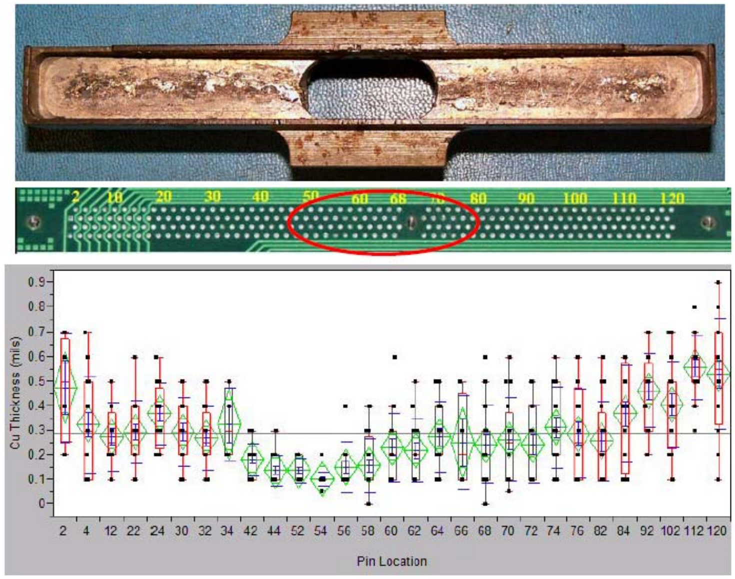

Figure 2 – Pin-to-Pin Variation in Copper Erosion

The statistical results of a design of experiment (DoE) confirmed that contact time is the most significant process variable affecting copper dissolution and the resulting copper erosion as can be seen in Figure 3 below[5]. The study showed that copper dissolution increases as cumulative contact time for both wave soldering and rework increases with an almost 100% dissolution of the barrel knee occurring after 47 seconds of contact time for Sn-Ag-Cu solder. The study indicated that pre-heat temperature and solder pot temperature for the range tested have minimal impact upon copper dissolution as can be seen in Figure 4 below[6]. However, solder wells at elevated temperature are known to rapidly accelerate copper dissolution.

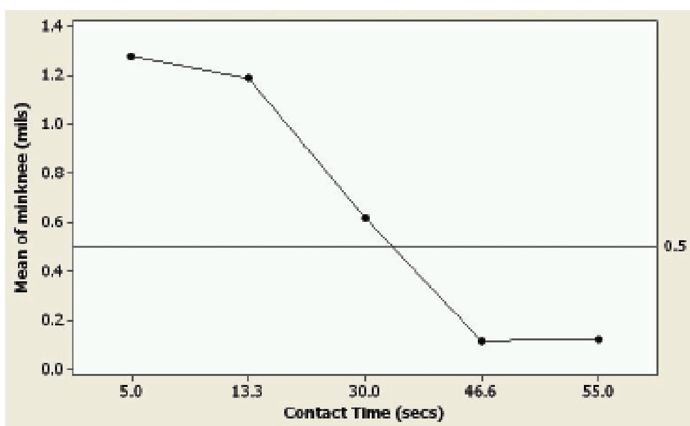

Figure 3 – Effects of Contact Time on Copper Dissolution

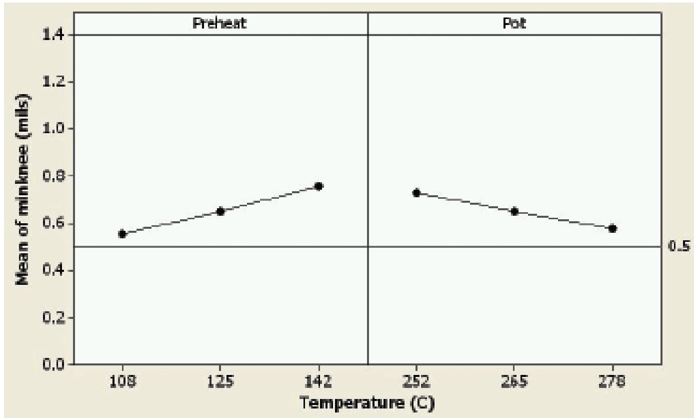

Figure 4 – Effects of Preheat and Solder Pot Temperature on Copper Dissolution

The results of the study showed that the apprehension over the impact of copper erosion is highly warranted when utilizing a static solder pot and potentially worse when using a fountain-based solder system equipped with a manifold type solder flow well in conjunction with elongated contact time during the lead-free soldering and/or rework processes.

Selective Soldering Process Optimization

One method to minimize copper dissolution is to utilize selective soldering for lead-free through-hole soldering in lieu of traditional wave soldering and its associated post-wave rework. To a lesser degree copper is dissolved from the circuit board pad and plated through-hole barrel during the selective soldering process. Virtually all board finishes experience this occurrence with the lesser exception of nickel/gold boards where the nickel acts as a barrier layer against dissolution of the copper. Because of the effects of copper dissolution, a routine analysis of the solder pot should be conducted to verify that maximum concentration levels do not exceed 1.0% by weight for copper (Cu), 0.02% by weight for iron (Fe), or 0.1% by weight for lead (Pb). The analysis frequency is dependent upon solder pot volume and the type of printed circuit board surface finish that is being processed.

The use of advanced solder delivery technology together with fully optimized selective soldering nozzles that employ design geometries with uniform solder flow dynamics results in minimal agitation of the molten solder and minimizes copper erosion. Examples of these selective solder nozzles employing this advanced solder delivery technology and uniform flow dynamics can be seen in Figures 5 and 6 below.

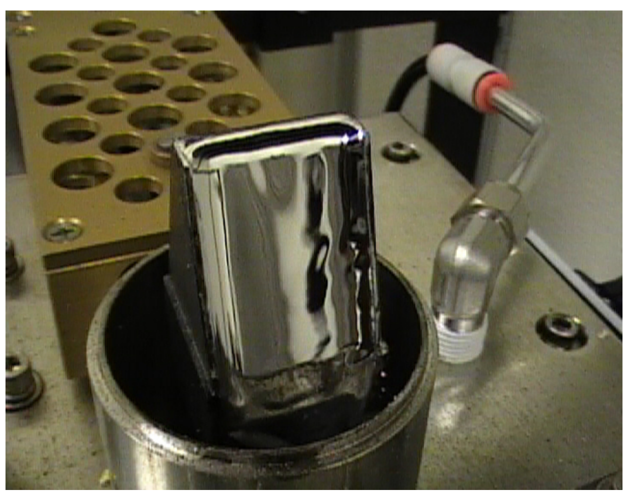

Figure 5 – Mini-Wave Solder Nozzle with Uniform Flow Dynamics

Figure 6 – 3 Inch Mini-Wave Solder Nozzle with Uniform Solder Flow

There are several key elements essential to successful lead-free selective soldering, among which are the impact of flux deposition, preheating techniques, solder application and solder nozzle design. The selection of a good flux is mandatory for lead-free soldering since lead-free solder alloys have lower wetting characteristics at a given processing temperature. Fluxes must be able to withstand topside board temperatures as high as 130ºC or higher and solder temperatures of 280ºC or higher for a minimum of 3-4 seconds of contact time.

Preheat temperature is critical for lead-free soldering with the best results obtained with topside board temperature in the range of 110-120ºC. Lower preheat temperatures are known to result in inadequate plated through-hole fill. Preheat temperatures need to be controlled so that thermal shocking of components does not exceed 100ºC as they enter the molten solder. Pre-heating of the printed circuit board assembly prior to the selective soldering process by itself is inadequate as the assembly cools during processing. Using topside preheat during the selective soldering process lessons the effect of thermal shock upon both through-hole components and the printed circuit board material and enhances topside solder fillet formation. The later is critical since laminate materials used for lead-free assembly such as FR 406, FR 410 and FR 305 are sensitive to elevated temperatures which can result in changing their rate of thermal expansion.

Mini-Wave Selective Soldering Advantages

Selective soldering provides improved solder quality and solder joint formation during first pass soldering by optimizing key process parameters on an individual component basis versus the traditional compromise of wave soldering. Because selective soldering is a highly controlled process, it maintains board integrity throughout the through-hole soldering process as well as during subsequent rework if any is required. Automated selective soldering also offers greater consistency of solder joint formation versus traditional wave soldering and post-wave rework as well as manual or hand soldering.

All of these benefits can be made available with simplified automation that reduces the direct labor cost of through-hole solder joint formation. An additional benefit of selective soldering is that a significant reduction in conversion cost including direct and indirect labor, consumables, equipment depreciation, throughput and process yield can be obtained by eliminating secondary operations normally required by wave solder or manual soldering operations. An example of this is the elimination of aperture wave soldering pallets and/or masking of a printed circuit board assembly prior to wave soldering which can be replaced with a multi-site selective solder nozzle. These multi-site nozzles can solder all pins of a through-hole component simultaneously as can be seen in Figures 7 and 8 below.

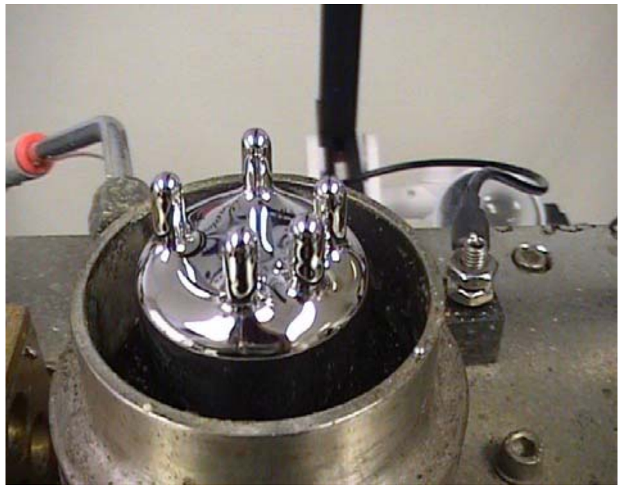

Figure 7 – Multi-Site Selective Solder Nozzle

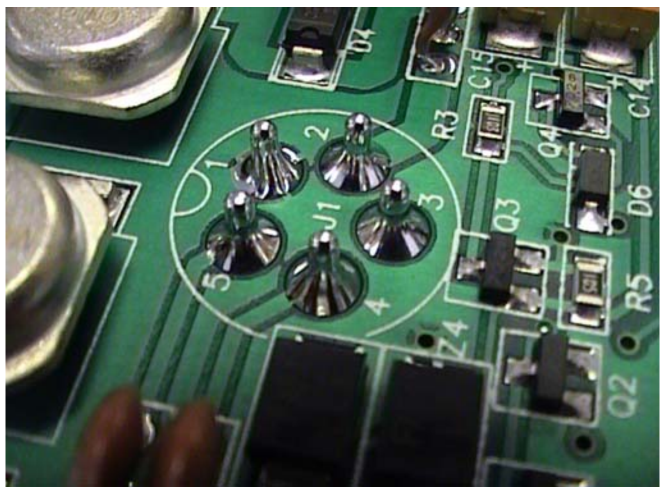

Figure 8 – Multi-Pin Automotive Electronics Display Cluster

There is a distinct value in, and positive reasons for, not moving the printed circuit board assembly throughout the selective soldering process. When using a wave soldering process with aperture pallets, top heavy components are susceptible to moving out of position requiring post-wave repair which is difficult if the component leads are partially inserted or worse if the leads are completely out of the board resulting in a plugged through-hole. Some robotic selective soldering machines that move the board suffer from the same effect. Only systems that do not move the board allows through-hole components to remain stable throughout the soldering process and eliminates the need to fixture components.

A crucial advantage in not moving the board during the soldering cycle is that sustained topside preheating can be used for lead-free soldering and/or high thermal mass components. Robotic-based systems that move the board during soldering cannot sustain topside board temperature throughout the soldering cycle and therefore require longer contact time which lengthens cycle time and increases the risk of copper dissolution.

Without the use of topside preheat, it is typical practice to use longer dwell times and/or higher solder temperatures, as high as 300-320ºC which causes copper erosion to become more pronounced. The use of sustained topside preheat is critical to ensure capillary action with lead-free solder alloys, especially with Sn-Ag-Cu and Sn-Cu-Ni solder alloys which wets and flows slightly better than most lead-free alloys.[7] Experience has proven that sustained preheat of the printed circuit board assembly during selective soldering greatly improves the wetting action of lead-free alloys. It has been determined that with the use of sustained preheat throughout the selective soldering process, the temperature of the solder pot can be decreased from 300-320°C to 260-280°C. Operating the solder pot at this lower temperature range reduces copper dissolution, produces less thermal burden on the components, and reduces energy consumption and oxide and dross generation.

The utilization of sustained topside preheat throughout the soldering process produces superior solder joint quality and increases productivity and is significantly advantageous to improving barrel fill and solder filet formation when soldering high-thermal mass components as can be seen in Figures 9 and 10 below.

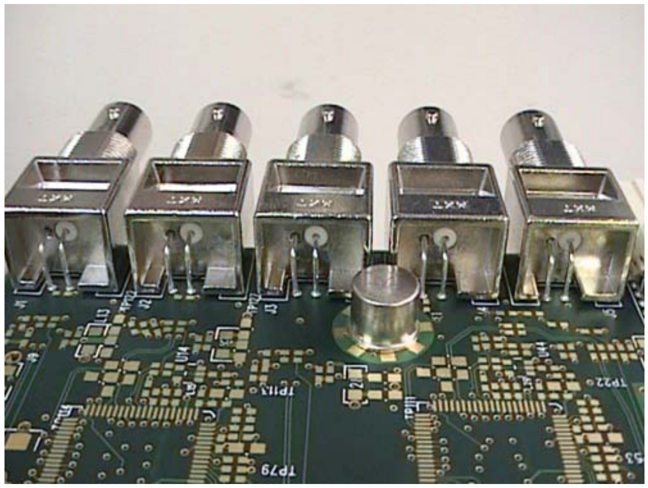

Figure 9 – High Thermal Mass RF Connectors

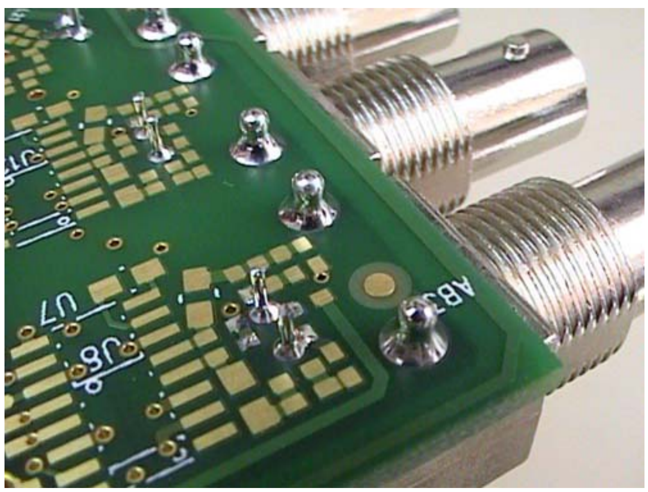

Figure 10 – High Thermal Mass RF Connector Solder Joints

The solderability of lead-free solder alloys is greatly affected by flux selection since the wetting characteristics of lead-free alloys are less than that typically exhibited by tin-lead alloys at a given process temperature. The flux selected must be able to withstand exposure to higher process temperatures required for lead-free alloys. Flux chemistries and flux application methods vary widely for selective soldering ranging from water-soluble fluxes and resin-free, no-clean fluxes to VOC-free fluxes and resin-based RMA fluxes. With the advent of lead-free, the use of VOC-free fluxes containing synthetic resin have gained in popularity due to the ability of synthetic resins to withstand higher preheat and soldering temperatures.

Unlike wave soldering, flux applied with the selective soldering process must not spread beyond the path of the solder nozzle so that the direct contact and heat of the molten solder will reduce ionic residue contamination and render the flux residues benign. Since the deposition of liquid flux onto the printed circuit board assembly must be precisely controlled, it is achieved by means of a drop-jet, aerosol or ultrasonic fluxer.

Drop-jet spray heads are advantageous for minimizing overspray with a spray pattern as narrow as 2mm and work well with alcohol-based fluxes, but are known to have incompatibility problems with water-soluble flux, rosin and resin-based fluxes, and fluxes that have solids content greater than 3%. Aerosol spray heads are more compatible with high solids fluxes with solids content of up to 35% or high rosin content flux but have a slightly wider spray pattern of 4mm. The best option is to have both drop-jet and aerosol flux application spray heads available on a common selective soldering machine platform.

This modular design provides precise on-demand application for all flux chemistries and can be easily switched via software control.

Multiple options are available for program generation of selective soldering systems including direct data entry, vision teach-in camera and downloading of computer aided design (CAD) files. Off-line programming by means of downloading a DFX or Gerber file provides fast program generation and minimizes machine downtime. An additional method to increase efficiency and flexibility is the use of an automatic component library in which sub-routines generate soldering patterns faster and are less error prone than manual program generation. Simultaneous movement of the Z-axis internal to the X and Y-axis travel minimizes non-productive machine time and speeds up the overall soldering cycle time.

Case Studies

In order to determine the actual cost savings and operational benefits derived from the implementation of lead-free selective soldering, the operation of several electronics manufacturing companies who have implemented selective soldering was studied. The area of study focused on the actual labor costs, throughput and quality improvement in their through-hole soldering operation. Numerous goals and objectives challenged these end-users during the conversion to lead-free selective soldering including:

1. Reducing the manufacturing time of the through-hole soldering operation from the present manual operation.
2. Reducing total soldering time to facilitate a 12% increase in production volumes without additional direct staff.
3. Improving operating efficiency and first pass quality by implementing machine repeatability and reducing reoccurring rework and repair.
4. Providing faster response time to customer special orders with automatic machine recipe setup.
5. Reducing the time required for through-hole soldering from the present mini-wave and hand soldering operation.
6. Improving operational efficiency and free up direct staff for other manufacturing cost centers.
7. Eliminating secondary operations of component and board prep and eliminate masking requirement.
8. Implementing no-clean flux chemistry minimizing flux residue and eliminating post-solder cleaning operation.

An immediate quality improvement and reduction in the solder defects was observed upon implementing automatic selective soldering by each of these end-users. Overall lead-free solder defects decreased between 20-30% with selective soldering as compared to the previous hand soldering method for one end-user while the other end-user noted a 10-15% decrease in solder defects from the previous mini-wave and hand soldering methods.

It is a competitive concern to minimize all of the cost factors required for a given assembly. It is also important that the measurement of conversion cost take into account all non-material factors including labor, consumables, equipment depreciation, throughput, maintenance, process yield and rework. The true cost of ownership extends far beyond the initial purchase price of capital equipment. In addition to equipment depreciation, key cost factors must be financially considered to arrive at an accurate conversion cost including the efficiency in terms of consumables consumption, performance in terms of net throughput, changeover and lost opportunity or non-productive time, reliability in terms of scheduled and un-scheduled maintenance and idle production, rework frequency and repair time, and tooling costs and plant utilities.

These case studies realized a substantial direct labor savings and reduction in conversion cost as a result of implementing selective soldering as displayed in Table 1 through 4 below.

Table 1 – Hand Soldering Conversion Cost, Case Study #1

Cost Factor	PCBA #1	PCBA #2	PCBA #3
Direct Labor-Hand Solder (Min.)	1.75	23.00	27.42
Direct Labor-Secondary Operations (Min.)	Included in above		
Direct Labor Cost per PCBA	$0.45	$5.94	$7.08
Consumables	$0.22	$0.24	$0.52
Capital Equipment	$0.06	$0.06	$0.06
Equipment Performance	$0.04	$0.04	$0.04
Equipment Reliability	$0.04	$0.04	$0.04
Inspection and Touch-up	Included in direct labor		
Tooling	$0.07	$0.15	$0.15
Floor Space/Utilities	$0.07	$0.07	$0.07
Conversion Cost per PCBA	$0.91	$6.54	$7.96

Table 2 – Selective Soldering Conversion Cost, Case Study #1

Cost Factor	PCBA #1	PCBA #2	PCBA #3
Direct Labor-Selective Solder (Min.)	0.50	4.50	6.00
Direct Labor-Secondary Operations (Min.)	Included in above		
Direct Labor Cost per PCBA	$0.13	$1.16	$1.54
Consumables	$0.12	$0.12	$0.12
Capital Equipment	$0.12	$0.12	$0.12
Equipment Performance	$0.02	$0.02	$0.02
Equipment Reliability	$0.04	$0.04	$0.04
Inspection and Touch-up	Included in direct labor		
Tooling	$0.00	$0.00	$0.00
Floor Space/Utilities	$0.14	$0.14	$0.14
Conversion Cost per PCBA	$0.45	$1.60	$1.98

Table 3 – Manual Soldering Conversion Cost, Case Study #2

Cost Factor	PCBA #1	PCBA #2	PCBA #3	PCBA #4	PCBA #5
Direct Labor-Manual Solder (Min.)	12.50	12.38	9.97	14.00	11.00
Direct Labor-Secondary Operations (Min.)	Included in above				
Direct Labor Cost per PCBA	$3.75	$3.71	$2.99	$4.20	$3.30
Consumables	$0.22	$0.24	$0.22	$0.24	$0.24
Capital Equipment	$0.10	$0.10	$0.10	$0.10	$0.10
Equipment Performance	$0.04	$0.04	$0.04	$0.04	$0.04
Equipment Reliability	$0.04	$0.04	$0.04	$0.04	$0.04
Inspection and Touch-up	Included in direct labor				
Tooling	$0.15	$0.15	$0.07	$0.15	$0.15
Floor Space/Utilities	$0.07	$0.07	$0.07	$0.07	$0.07
Conversion Cost per PCBA	$4.37	$4.35	$3.53	$4.84	$3.94

Table 4 – Selective Soldering Conversion Cost, Case Study #2

Cost Factor	PCBA #1	PCBA #2	PCBA #3	PCBA #4	PCBA #5
Direct Labor-Selective Solder (Min.)	3.15	3.25	1.03	4.42	2.50
Direct Labor-Secondary Operations (Min.)	Included in above				
Direct Labor Cost per PCBA	$0.94	$0.97	$0.31	$1.32	$0.75
Consumables	$0.12	$0.12	$0.12	$0.12	$0.12
Capital Equipment	$0.12	$0.12	$0.12	$0.12	$0.12
Equipment Performance	$0.02	$0.04	$0.02	$0.02	$0.02
Equipment Reliability	$0.04	$0.04	$0.04	$0.04	$0.04
Inspection and Touch-up	Included in direct labor				
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00
Floor Space/Utilities	$0.14	$0.14	$0.14	$0.14	$0.14
Conversion Cost per PCBA	$1.38	$1.43	$0.75	$1.76	$1.19

Based upon the above case studies, the implementation of automated selective soldering significantly reduced through-hole soldering time, improved first pass quality yields and eliminated indirect secondary operations resulting in reduction in conversion cost of between 51% and 78% on an individual printed circuit board assembly basis.

In review, the benefits derived from implementing lead-free selective soldering for these case studies included:

1. Consistent solder joint quality within all customer and industry acceptance criteria irrespective of human intervention.
2. A significant reduction in repetitive rework and repair for the effected production quantities.
3. A marked improvement in equipment, facility and human resource utilization.

Conclusion

Although the economic cost savings are substantial, the true benefit of implementing selective soldering is realizing a greatly reduced defect rate and a significant improvement in conversion cost as compared to traditional wave soldering, post-wave rework and/or manual soldering in a lead-free environment. Several case studies have confirmed that substantial reduction in operating costs and improvements in first-pass quality are attainable with selective soldering, thus decreasing overhead, improving operating margins and increasing competitiveness.

Selective soldering also offers a significant advantage over the use of a static solder pot or fountain-based solder system with respect to minimizing the effects of copper dissolution and the resulting copper erosion.

References

1. Figure 1: source: Celestica Incorporated
2. Ma, L., Donaldson, A., Walwadkar, S. and Hsu, I., "Reliability Challenges of Lead-Free (LF) Plated Through-Hole (PTH) Minipot Rework," IPC/JEDEC Global Conference on Lead-Free Reliability and Reliability Testing for RoHS Lead-Free Electronics, April 2007
3. Seelig, Karl, "Considerations for Lead-Free Wave Soldering," AIM, Internal Document, June 2005
4. Figure 2: source: Intel Corporation
5. Hamilton, Craig, Kelly, Matthew and Snugovsky, Polina Ph.D., "A Study of Copper Dissolution During Pb-Free PTH Rework Using a Thermally Massive Test Vehicle," Circuits Assembly, May 2006
6. Figures 3 and 4: source: Celestica Incorporated
7. Klenke, Bob, "Lead-Free Selective Soldering: The Wave of the Future," Proceedings of SMTA International Conference, September 2002
8. Figures 5, 6, 7, 8, 9 and 10: source: ACE Production Technologies, Inc.