Applied Research for Optimizing Process: Parameters for Cleaning Pb-Free Flux Residue

Dirk Ellis
Speedline Technologies
Camdenton, MO

Mike Bixenman
Kyzen Corporation
Nashville, TN 37211

Abstract
As the electronics industry moves toward the implementation of Pb-free soldering, the impact on the assembly process must be considered. One process that is often over looked is the cleaning of assembled printed circuit boards. How will the introduction of lead free material impact the cleaning process?

A number of studies have proven the poorer wetting of SAC 305 alloys and many of the other Pb-free alloys as contrasted to Sn/Pb during the soldering process. To address this issue, solder paste manufacturers researched and advanced flux technologies to improve soldering yields. Many of the advanced flux technologies employ modern "exotic" compounds, which often increase the difficulty of removing post-soldering residues. It is evident that both cleaning equipment and cleaning chemistry must be modified to enable effective and consistent cleaning of Pb-free flux residues. It is also evident that the best overall cleaning solutions will be provided by cleaning equipment and cleaning material companies working together to optimize their products.

This paper discusses extensive cleanliness testing of over 70 Pb-free soldering materials. The data suggests increased difficulty when cleaning Pb-free post-soldering residues. Based on the data, this paper discusses advances in cleaning material and cleaning equipment mechanical designs that will optimize the cleaning of Pb-free flux residues. This paper will detail the changes made in the cleaning equipment for optimizing the cleaning material advancements in industry standard cleaning equipment.

Introduction
The early initiative and designed experiment to study the cleaning Pb-free flux residues occurred in 2000-2001 time frame. Most solder paste manufacturers participated in the study by submitting their Pb-free solder pastes. Printed circuit boards were printed, reflowed and cleaned using aqueous inline, semi-aqueous centrifugal and vapor degreasing technologies. The data found the Pb-free residue harder to clean due to the higher reflow temperatures, higher flux capacity, and more tin-salt formation. The flux composition categories consisted of no-clean soft residue, water-soluble residue, and no-clean hard residue. The results and findings led us to believe that Pb-free flux residues would be more difficult to clean but cleanable using the then existing cleaning technologies and processes.

Cleaning study publications over the past two years suggest that Pb-free will be more difficult to clean but with the improvements in cleaning chemistry and mechanical designs, Pb-free assemblies will be successfully cleaned. Recently a number of prospective customers have qualified Pb-free solder pastes and submitted boards for cleaning validation. To successfully clean many of the no-clean soft and hard flux residues required increased aqueous cleaning concentrations, longer wash times, and higher processing temperatures[2]. Most Pb-free water soluble pastes required cleaning additives to successfully clean. Additionally, aqueous batch processing that use higher flow and less direct impingement was unsuccessful in cleaning some of the more popular solder paste flux residues. The findings point to the need for improved cleaning chemistry and mechanical designs.

Problem Statement
Increased functionality and higher clock speeds demand tighter dimensions, which create substantial cleaning challenges. Removing residue from fine pitch, peripheral and area array components requires improved mechanical impingement and flow. Additionally, flux residue under chip caps, often mounted flush to the circuit board, presents a demanding cleaning challenge. The problem is that cleaning Pb-free flux from high density circuit assemblies using existing legacy cleaning processes often will not achieve the desired result. Not only is Pb-free harder to clean but there is more residue as compared to standard no-clean eutectic Sn/Pb alloys. Figures 1 & 2 illustrate the amount of Pb-free water soluble and no-clean flux residue before cleaning processes.

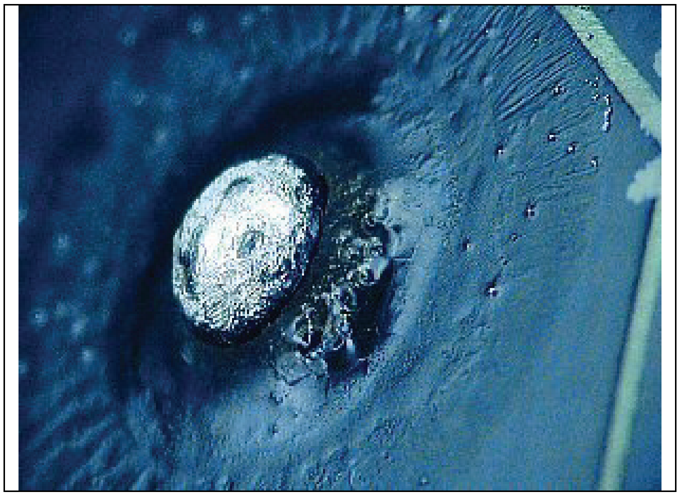


Figure 1 - Pb-Free Water Soluble Flux Residue

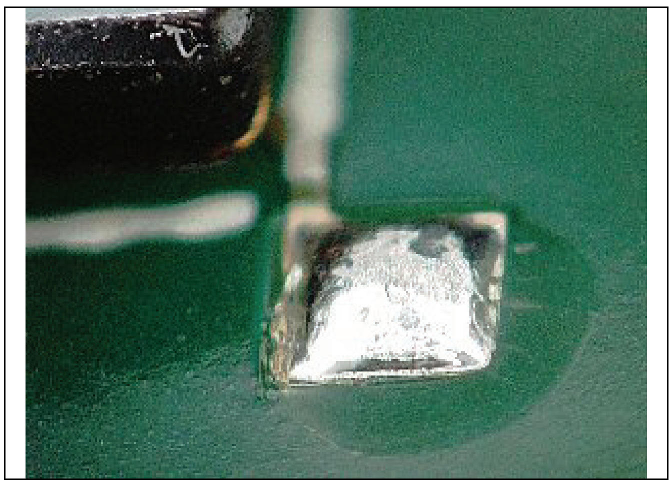


Figure 2 - Pb-Free Low Residue No-Clean Flux Residue

As solder material developers address challenges such as wetting, no clean, OA and RMA flux packages; the flux compositions are becoming more sensitive to the reflow process. It is well documented that the reflow process has a direct, often dramatic affect on the difficulty of cleaning post soldering residues. The reflow profile has now become more critical and the manufacturers reflow profiles should be adhered to closely. Choosing between the two traditional profiles, ramp to spike and soak will need careful consideration as well. With eutectic Sn/Pb, the soak profile aided the flux activation process, however with Pb-free the soak allows more carriers/solvents to evaporate, potentially affecting cleaning. As the profile reaches the spike zone, the delta T and time above liquidous become far more critical to how, and sometimes if the residue can be successfully cleaned. These higher heat and exposure time conditions convert the flux residue into a hard clear shell.
The straight ramp profile appears to be somewhat more favorable for cleanable Pb-free post soldering residues. The gradual increase in temperature does not allow the carriers to be boiled off as quickly, yielding softer and more cleanable residue. Figure 3 illustrates a Pb-free ramp to spike reflow profile.

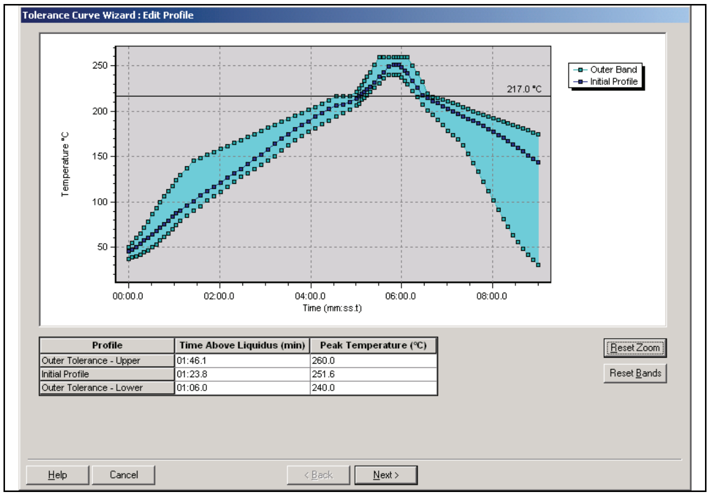


Figure 3 - Pb-Free Ramp to Spike Reflow Profile

Image courtesy of Plexus Corporation

Recent Pb-free cleaning trials processed boards using both the ramp to spike and soak profile. The boards build using the soak profile left a clear flux pattern around the solder leads. After close investigation, the residue penetrates into the solder mask and leaves a clear pattern from the flux residue. Figure 4 illustrates the soak profile while figure 5 illustrates the clear flux outline around the solder leads.

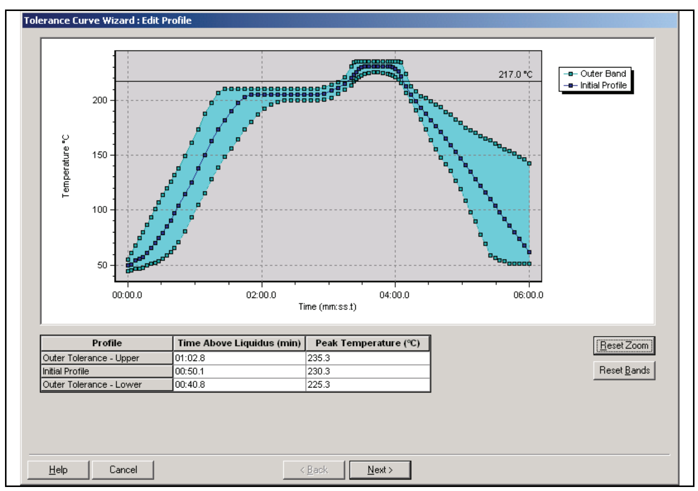


Figure 4 - Pb-Free Soak Reflow Profile

Image courtesy of Plexus Corporation

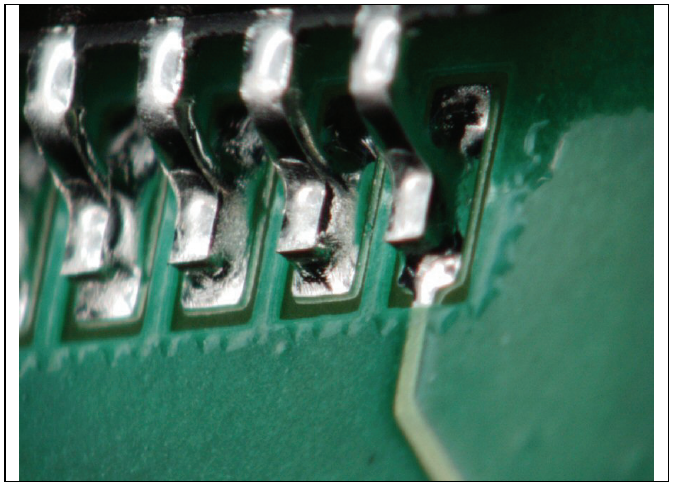


Figure 5 - Clear Flux Outline after Cleaning Pb-Free Soak Profile Circuit Board

Ellis and Bixenman's (2004) research indicated that a nitrogen inerted environment prevents the flux residue from degassing and forming a hard residue[1]. For some hard residue Pb-free materials, we believe that a nitrogen inerted environment will improve clean ability. Nitrogen removes the oxygen from the process that reduces excessive oxidizing and charring of the residues at the elevated Pb-free spike zone temperatures.

The reflow of double sided PCBs will further challenge the cleaning process as the first side residues go through two temperature excursions. In extreme cases, this may require each side to be cleaned after reflow much like the current eutectic OA process.

As more and more Pb-free cleaning tests are run, the data continues to point to the word "more." More thermal energy, more chemical energy and more mechanical energy appear to be desirable and in some cases required. As component/package sizes decrease, along with standoff height and pitch, I/O count increases; how will we accomplish the same cleaning results with Pb-free? Can machine manufactures invent new and better ways of delivering mechanical energy to the board surface? Can chemical suppliers develop better chemistries?

Mechanical Driving Forces

As customers demand faster process cycles and shorter machine lengths, how can machine manufactures accomplish more with less? In this world of rapid change, the only constants are the laws of physics. These laws are unavoidable, and often limit us from doing more with less. Equipment manufactures should study these laws down to the n^{th} degree, but at the end of the machine, what matters to you is that you have a clean board to deliver to your customer. So how can we best optimize the mechanical energy that is delivered by the equipment? Perhaps by efficient conversion of the pump horsepower into impact energy that is maximized at the board surface at the right time.

Inline spray in air machine testing has shown a relationship between mechanical energy and chemical energy that can be approximated by the 80/20 rule. Nozzle selection and pattern design, including contact time have been validated as dominant variables particularly with the more discriminating Pb-free residues. The nozzle spray patterns commonly employed in today's cleaning equipment fall into two categories dispersed (fan, delta, conical) and focused solid stream (coherent). The energy delivered to the board by focused nozzles is approximately 20 times more than what dispersed flow nozzles deliver. However, each nozzle type plays an important role. The dispersed patterns are particularly effective for providing thorough contact and soaking that allows board temperature to rise while allowing the chemistry additional contact time to interact with, solubilize and soften the residues. The focused solid stream nozzles provide high surface energy required to displace residues freed from the surface by the wash chemistry. Innovative design and configuration development utilizing both nozzle and chemical cleaning energies work in concert and allows for successful residue removal.

Taking this relationship to the next level or sublevel, how do the nozzles work in cleaning not just surface residues around components and pads, but residues under all the different components types found on today Pb-free SMT assemblies? Is it possible to find a combination and timing of nozzle patterns at optimum pressures and flow rates that can 100% clean every SMD type? What is your most difficult component to clean, 1825 capacitor, micro BGA, BGA or flip chip? This paper will look at several nozzle combinations and their different timings and their cleaning results.

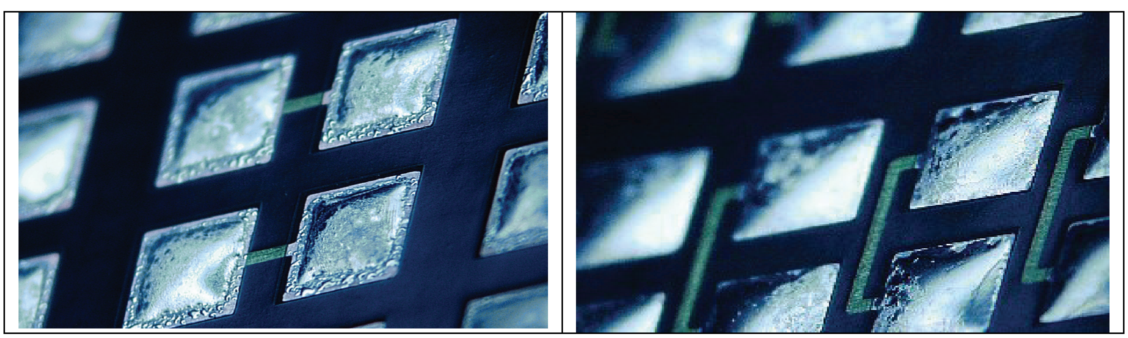
Chemical Driving Forces

Engineered cleaning fluids use chemical driving forces that allow different functional properties to occur during the cleaning process. Known art developed in the 60s used aliphatic amine compounds to saponify rosin flux residue. The chemical reaction converts the rosin flux, in the presence of heat with an aliphatic amine, into an alcohol and the amine salt of the carboxylic acid. The water soluble reaction product is easily removed with hot water using spray impingement. As low residue no-clean fluxes entered the market, modified resins required increased solvency combined with mild saponification to effectively clean.

Legacy aqueous cleaning fluids developed 5 - 15 years ago targeted flux compositions designed first for traditional rosin fluxes and eventually for eutectic no-clean flux soldering. These cleaning fluids were innovative, disruptive technologies for the then "dominant" cleaning fluids such as semi-aqueous, vapor degreasing and aqueous saponified. The new technologies functioned by forming high solvency in an aqueous medium. These cleaning process advancements allowed aqueous cleaning to become the dominant choice for process cleaning at the manufacturing floor. Two divergent approaches targeted cleaning using water soluble contrasted with water insoluble oxygenated compounds. Both were highly effective at cleaning a wide range of flux residues.

Pb-free soldering posed a number of challenges that required innovation in the flux compositions to resolve. High Sn (tin) alloys do not wet and self-center like eutectic Sn/Pb metallization. Additionally, the metallized structure can be grainy and dull in appearance. Recent solder paste development addresses these design limitations, providing a solder bump with similar appearance and performance to eutectic Sn/Pb. From a cleaning fluid design perspective, the first objective identifies materials that dissolve these residues. The research question moves back to chemical driving forces needed to achieve dissolution. Are the driving forces more effective through solvency or reactivity?

To address the research question of solvency as compared to reactivity, designed experiments were used to understand the cleaning contribution of each material. Selected Pb-free materials do show a positive correlation to reactivity. Building higher reactive cleaning solutions routinely comes with many trade-offs, some of them severe in the form of solder bump attack and compatibility constraints. Additionally, highly reactive cleaning agents are corrosive, which often requires the use of additives to protect the finish of the assemblies. In some particularly restrictive regulatory environments rinse water neutralization may be required prior to taking rinse water to drain. When considering these design limitations, higher reactive cleaning agents should be considered as a last option. Figure 6 illustrates a Pb-free solder bump with a dull appearance when using a highly reactive cleaning solution as compared to a solder bump when using solvency as the chemical driving force.



(a) (b)

Figure 6 - Solder Bump Appearance when using: (a) Highly Reactive compared to (b) High Solvency Cleaning Fluids

Once the surface residue driving forces are achieved, the next design criterion that must be considered is surface tension. High density components have tighter standoffs to the board surface. Pb-free flux residue forms a flux dam under the part. The cleaning fluid must flow under the component to effectively remove the flux residue in the short amount of time allotted to the wash section during the cleaning process. To achieve this objective, surface active agent technology is needed to form a microscopic droplet with a very thin wall. Additionally, Stach and Bixenman's (2005) research found that cleaning soon after reflow improves cleaning under flush mounted components[4]. The more time that elapses between reflow and cleaning, the greater the probability that increased time in the cleaning fluid will be needed to successfully clean.

Purpose Statement

Stach and Bixenman's (2004) research studied the optimization of cleaning energy in batch and inline spray cleaning systems[3]. The objective of mechanical cleaning systems is to reduce time by increasing energy delivered to the board surface. Maximizing the physical energy delivered to the surface increases the dynamic cleaning rate. An optimized cleaning system requires the proper balance of chemical and mechanical driving forces. The chemical driving forces must rapidly solublize and penetrate under low standoff components. Cleaning is in some ways a function of flow across the part being cleaned. Therefore, the chemical driving forces must form a thin and weak droplet that allows the cleaning fluid to move in and out of tight spaces. Additionally, spray nozzle jets deliver energy to the surface of the part being cleaned. The design and configuration of the nozzles becomes important in optimizing the cleaning system.

To optimize a Pb-free cleaning process, cleaning equipment and cleaning chemistry manufacturers must collaborate to design improved cleaning equipment and cleaning fluids. Stach and Bixenman (2005) reported that the timing and sequence of events in a cleaning process are critical. Each section or step in the process requires careful thought, understanding and solid design. The pre-wash should thoroughly wet the parts with the wash chemistry and provide sufficient flow and contact time to bring the assembly to wash temperature. This facilitates reaching the full static-cleaning rate while softening the residues. In the wash zone, the part should see several high impingement scourgings, punctuated by brief soak periods. This optimizes the static rate by maintaining fresh cleaning fluid on the part and optimizes the dynamic rate by focusing the maximum physical energy at the part surface. The purpose of this designed experiment is to contrast the cleaning effectiveness of two eutectic Sn/Pb hard residues with two hard residue Pb-free materials. The Pb-free pastes selected are two of the most difficult materials to clean. The test vehicle uses a 3 mil standoff with paste flux reflowed under the die. A high solvency cleaning fluid designed for Pb-free while comparing fan versus coherent spray patterns.

Research Methodology

Quantitative methods discover themes and explore patterns, describe the problem, and predict an outcome. In this experiment, the research compared two eutectic low residue solder pastes and two Pb-free low residue solder pastes. Figure 7 illustrates the test vehicle, a glass slide at a 1"x1" glass die using a 3 mil standoff. The flux was dispensed on two sides of the glass die and reflowed using a eutectic profile for the Sn/Pb paste and a ramp to spike Pb-free profile for the Pb-free paste. The cleaning solution temperature was fixed at 140ºF. An aqueous inline cleaning machine using both fan and solid stream coherent nozzles in the wash and delta nozzle in the high pressure wash zone was employed. The cleaning fluid tested utilized high solvency combined with low reactivity. This factorial experiment evaluates the variables of time with belt speeds of 1, 1.5, 2, and 3 feet per minute; fan and coherent wash nozzles; and cleaner concentration. Table 1 summarizes the test variables.

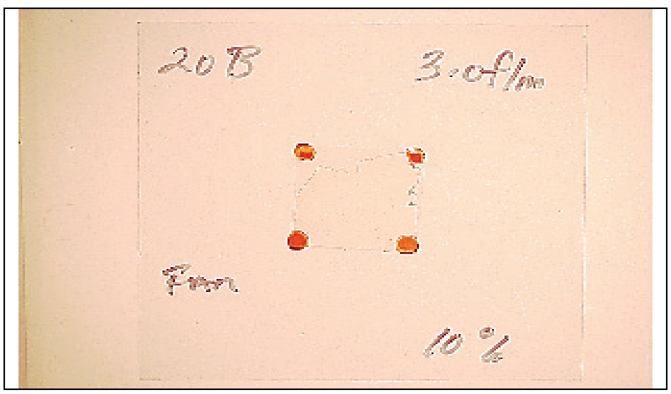


Figure 7 - Test Vehicle

Table 1 - List of Variables Tested

Chemistry Concentration	10%
	15%
	20%
Wash Spray Nozzles	Fan
	Coherent
Temperature	140ºF
Conveyor Belt Speed	1 foot per minute
	1.5 feet per minute
	2.0 feet per minute
	3.0 feet per minute

Data Findings

Charts 1 & 2 reflect the eutectic Sn/Pb paste fluxes and charts 3 & 4 reflect the Pb-free paste fluxes. A first glance review of the data reveals a striking contrast to the cleaning difference from the eutectic paste fluxes as compared to the Pb-free paste fluxes. The Pb-free fluxes were much harder to clean. The data indicates that longer time in the wash section improves cleaning performance. The data indicates that the JIC nozzles improved cleaning performance under low standoff components. The data does not conclusively indicate that higher cleaner concentrations improve performance.

Chart 1: Eutectic Paste Rosin Flux #1

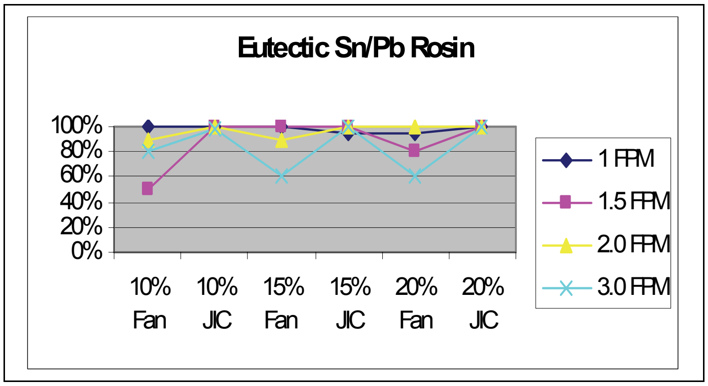


Chart 2: Eutectic Paste Hard Residue Flux #2

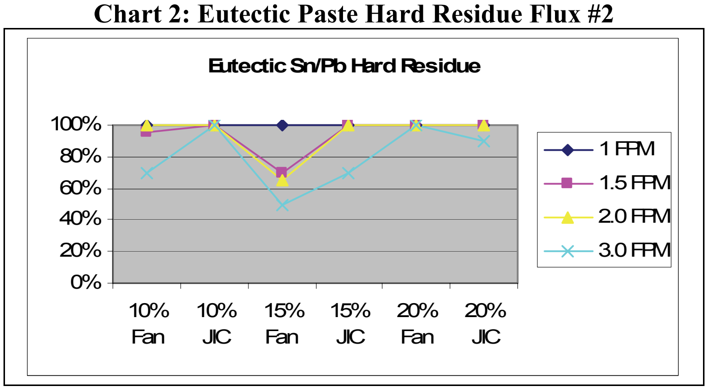


Chart 3: Pb-Free Hard Residue Paste Flux #1

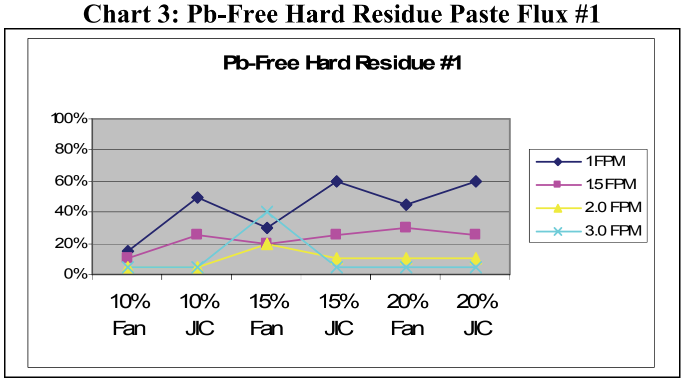
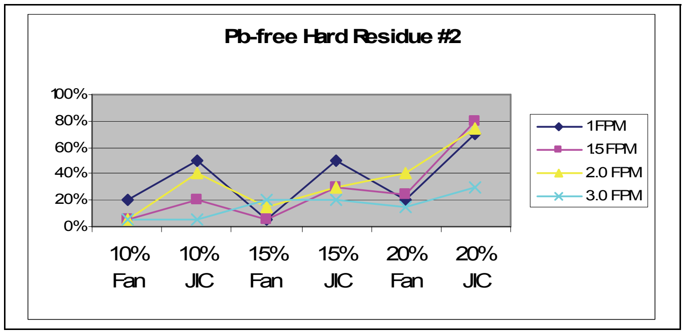


Chart 4: Pb-free Hard Residue Paste Flux #2



Conclusions and Recommendations

The data points to Pb-free as being harder to clean. The research continues to push toward the need to innovate advance chemical fluids and improved mechanical designs. We do know that water-soluble, soft residue and many hard residue Pb-free solder pastes are cleanable with existing cleaning fluids and mechanical designs but process parameters must be adjusted for most hard residue fluxes. The common parameters used for eutectic Sn/Pb cleaning in an inline cleaning machine process are as follows: 10-30% cleaning concentrations; 2-3 ft/min belt speed; and 120-160ºF wash bath temperature. Pb-free cleaning data infers that higher processing temperatures are commonly needed; lower belt speed is often required; and higher cleaner concentrations are often needed. Charts 5& 6 illustrate the improvement in cleaning when using higher processing temperatures and concentrations along with both solid stream and sheet coherent nozzles. The data continues to point to a narrower process window with process parameters being pushed to the high end of the spectrum.

Chart 5: Pb-free Hard Residue Paste Flux #1

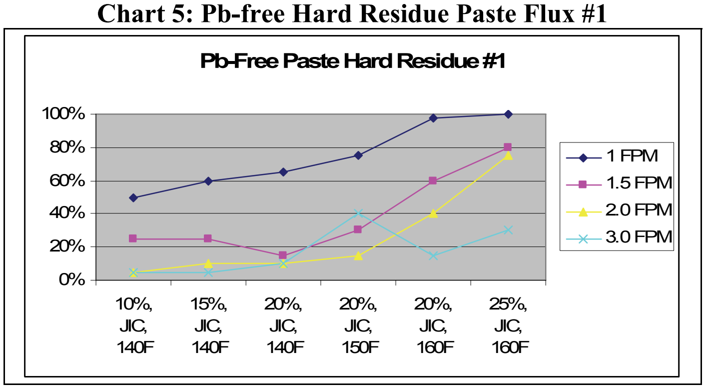
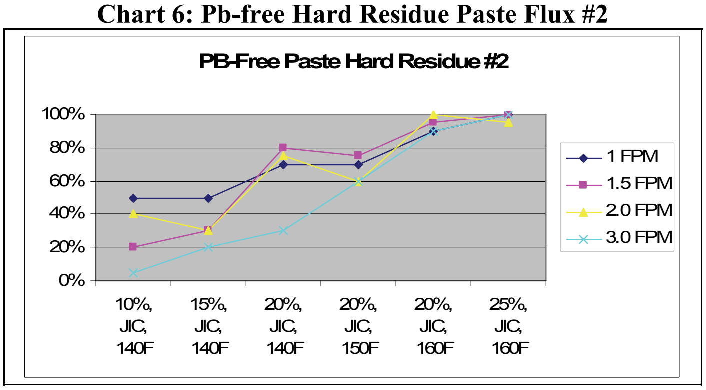


Chart 6: Pb-free Hard Residue Paste Flux #2



Pb-free points to changing assembly floor manufacturing processes. To address this change, cleaning chemistry manufacturers must continue to evolve their product offerings in response to the near continuous stream of new technology being introduced by the solder paste manufacturers. Early generation Pb-free materials often employed eutectic flux compositions into their Pb-free products. Performance was poor, which lead these companies to research and develop new flux compositions to meet the needs for improved wetting, thermal stability, and solder appearance. This development cycle has only accelerated in the past 2 or 3 years. The same must be true for cleaning chemistry suppliers. The products of the past may work but companies must run them at higher concentrations, longer wash times, and higher processing temperatures. This equates to higher processing costs and lower efficiency. For operators to retain the competitive cost advantage of their cleaning process, migration from legacy cleaning technologies to modern cleaning equipment and materials will be an essential step in reducing cost of ownership even further.

The data infers that solid stream JIC and sheet coherent nozzles in the wash improved cleaning performance. Mechanical designs in cleaning machines need to drive cleaning fluids underneath components to help solubilize vehicle used. Dispersed nozzles could not accomplish this task even at higher temperatures and concentrations. Coherent nozzle technology that has been employed in the cleaning industry for the past 20 years still proves its necessity for cleaning Pb-free residues.

Follow on research is underway to develop improved cleaning fluids that operate at lower concentration, temperatures under 150ºF, and conveyor belt speeds in the 1-2 ft/min range. To accomplish such this task, research and development personnel are working closely with application testing lab personnel, customers, solder paste companies, and equipment companies. Forming collaborative working relationships shortens the product development cycle while also focusing on the designs on areas of critical importance. Additionally, solder paste companies are considering cleaning more when designing new generation solder pastes.

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Authors

Mike Bixenman is Chief Technology Officer for Kyzen Corporation. Kyzen Corporation is a market leader for electronic assembly and advanced packaging engineered cleaning materials. mike_bix@kyzen.com

Dirk Ellis is an Cleaning Application Engineer for Speedline Technology. Speedline Technology is a market leader for cleaning equipment designed to meet the emerging cleaning needs for electronic assembly and advanced packaging market segments. delis@speedlinetech.com