"IC Packaging Trends Causing Concerns in Complete Flux Removal"

Rich Brooks
Kyzen Corporation
430 Harding Industrial Drive
Nashville, TN 37211
615-983-0888
Rich_brooks@kyzen.com

Abstract

The complete cleaning and removal of flux / soil residues under low profile components (especially flip-chip devices) are becoming more critical, especially as the conductor spacing's decreases and the power increases. The reliability of the circuit can be greatly affected when residues are not completely removed.

Flip chip bump pitch and die size push packaging trends resulting in tighter and smaller spaces underneath the devices. A majority of flip-chip assemblers are using water soluble fluxes and they typically use only DI water to remove the flux residues. Because of the tighter spaces and increased I/Os, the complete removal of these water soluble flux residues are becoming more difficult. Due to the ionic nature of water soluble flux residues all residue must be removed to prevent a pathway for electrochemical migration and acceptable bonding of the underfill material.

To insure that all of the flux residues are being removed from under the package, cleaning chemistries must be used. Cleaning chemistries provide the polarity and hydrogen bonding forces needed to remove oxidized flux while lowering surface tension to improve penetration under the die. The cleaning agent design must also be matched with the cleaning equipment.

To completely remove flux residue under the IC packages, the cleaning equipment's dynamic energy must also be studied, along with the cleaning chemistry. Additionally, both the cleaning chemistry and equipment must be matched up with the flux residue that is being removed. This paper will evaluate various cleaning chemistries and cleaning equipment that provide the best cleaning performance for very low package stand-offs and tighter pitch devices, as well as the different flux residues and process parameters.

Key words: Cleaning, IC Packages, flip-chip device, water soluble flux, flux residue

Introduction

New IC and flip-chip package technologies increase the cleaning complexity. The number of active sites along with reduced bump pitch is proportional to the number of I/O. And with the increase I/O and reduce bump pitch, the package Z-Axis is significantly decreased. Flip-chip packages with less than 1mil stand-off height are common place. Innovative package designs create more demand for these new technologies. The need to effectively remove flux residues is becoming more critical while failure to adequately clean impacts yields and reliability.

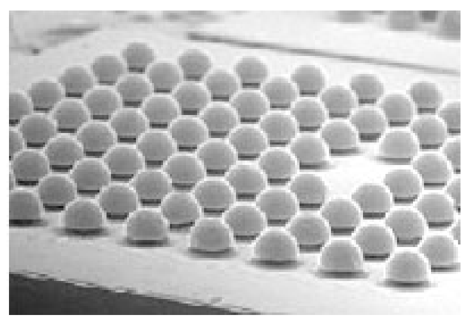

Figure 1 – Flip-Chip device

Packagers have been soldering flip-chip devices for years using water soluble fluxes and then cleaning using only water. One of the key motivations for using water soluble fluxes is due to complexity and difficulty in cleaning all residues from under the die. When soldering thousands of small interconnects, water soluble flux activity is an additional plus.

Cleaning with water does have its limitations. One issue is the inability to dissolve and displace oxidized flux residues. Additionally, water has a surface tension of approximately 70 dynes/cm preventing water from penetrating under devices below a 3-mil stand-off. This has been proven in past papers and presentations. Fine particle spraying of water can protrude under smaller gaps than three mils but will also have its limitations (such as complete removal and drying). Water with additives is a more effective flip chip cleaning option. Engineering in materials that match up to chemical nature of the residue open the process window. The small addition of chemistry to water also reduces the surface tension to below 30 dynes/cm, and thus making the cleaning process significantly easier.

5-CLEANING FORCES

Five forces that directly influence the cleaning properties of flux residue are the solder flux, heat exposure, component gap, cleaning agent, and cleaning equipment (Figure 2). Variations in any of these factors can and does influence the cleaning rate.

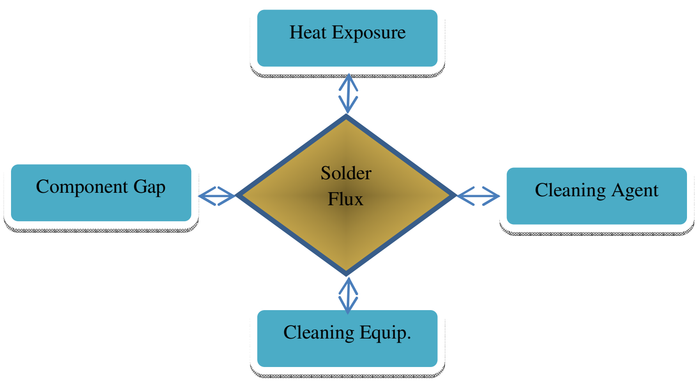

Figure 2: Five Cleaning Forces

Soldering Flux

Solder alloys rapidly oxidize upon exposure to air, moisture, and heat.[1] Oxidation, caused by exposure to oxygen in air, results in a non-conductive and non-solderable metallic surface. Solder flux is a chemical cleaner that removes oxidation from metal surfaces, facilitates wetting, and improves metallurgical bonding. When flux is heated, low boiling constituents within the flux evaporate, flux activators remove surface oxidation, and oxygen barriers (rosin/resins/water soluble polymers) protect the alloys from re-oxidation during the solder process. During the soldering process, heating and cooling ramp rates must be compatible with the assembly and components. Exposure to high temperatures must be defined and maintained.[2]

The soldering process can be affected by the mass of the associated component, proximity and mass of neighboring components, the size of the pads, and the amount of heat that travels through the tracks and boards.[2] These factors increase demands on the flux, which has a significant influence on quality and low defect soldering rates. This task becomes more difficult with highly dense miniaturized designs and lead-free soldering. To address these complexities, the flux must be stable to high temperatures; resist charring, oxidation and burning; and provide a resistant oxygen barrier.[3] These properties change the solubility and cleaning properties of flux residue post soldering.

Flux and cleaning agent advances over the past 20-years have kept pace with component and board assembly technology advances. Rosin, low-solids, no-clean, and water soluble flux technologies designed for eutectic tin-lead were readily cleanable even after multiple soldering processes. The same ***cannot*** always be stated for lead-free soldering. Miniaturization and lead-free soldering require more active and stable flux compositions that remove oxidization with less flux, wet higher surface tension alloys, and protect the underlying metal from oxidation during the soldering process. The cleaning properties of lead-free flux compositions, including water soluble, have changed. The residues are harder and require more active cleaning agents and mechanical to remove the flux residues.

Heat Exposure

The reflow process heats the package plus components held by solder paste through successively higher temperatures. The solder profile progressively starts by evaporating flux volatiles, initiates flux activation, raises the components to be joined to a temperature which is sufficiently consistent for the solder to flow evenly onto all surfaces, and reflows the solder paste over board finishes to facilitate solder connections. Temperature excursions and the time exposed to liquidus solder temperatures influence cleaning properties.

Excessive exposure to the soak and liquidus stages can oxide (char), crosslink (polymerize) and harden flux residues. Figure 2 illustrates a lead-free solder profile using a soak process near liquidus. A long soak profile ensures that the solder paste is fully dried before hitting reflow temperatures. In this example, the heat generated from the flux activation zone may oxidize or cross-linked the flux residue (Figure3). To clean this residue, an aggressive cleaning condition is needed. In some cases, the cleaning process window is quite narrow, resulting in highly inconsistent cleaning.

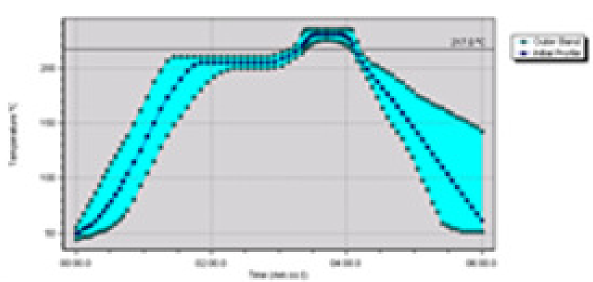

Figure 2: Soak Reflow Profile

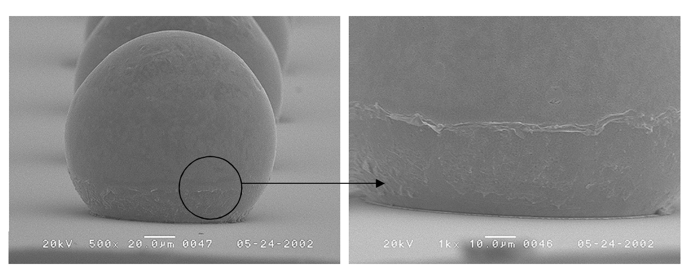

Figure 3: Oxidized Flux Residue

Optimal soldering processes are hot enough to enable the solder to wet the board and components yet cool enough not to damage the items being soldered and a controlled cool down to ensure solder joints are sound.[2] Defining the exposure to high temperature requires heating and cooling ramp rates that are compatible with the solder paste, components, board finishes, and cleaning process. Figure 4 illustrates a ramp to spike lead-free solder profile using the same solder paste illustrated in Figure 2. Reduce heat exposure rendered a cleanable flux residue.

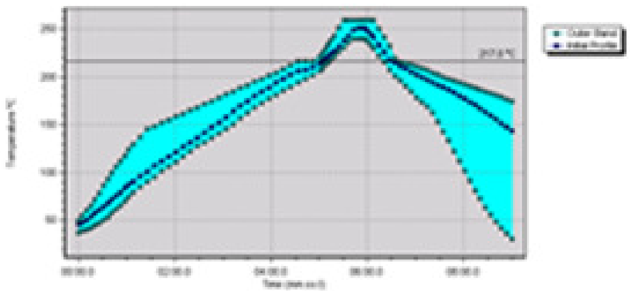

Figure 4: Cooler Reflow Profile

Component Gap

Component miniaturization decreases the spacing between conductors. During solder reflow, flux under fills the bottom side of the component (Figure 6). The distance from the board surface to the bottom side of leadless components is consistently less than 2 mils. For cleaning to occur, the cleaning agent must first wet the residue. To sufficiently wet the residue, the cleaning process must break through the flux under fill to create a flow channel.

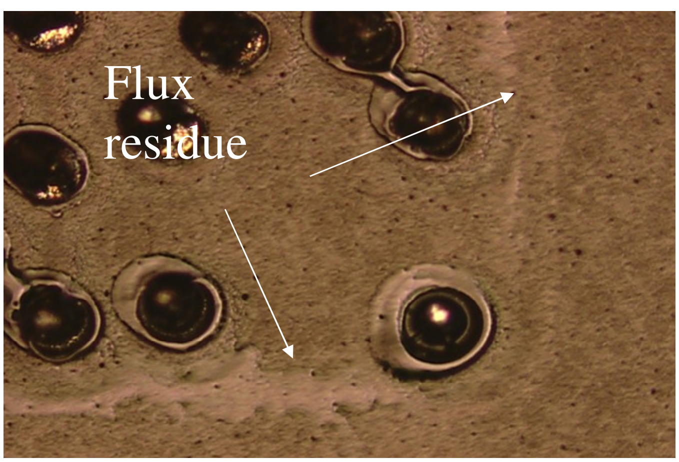

Figure 6: Flux Residue under Die

Cleaning under low gap components is increasingly more difficult due to larger die size and the number of interconnects under the die. A higher density of flux residues reside next to each soldered connection. Flux residues that flow away from the solder interconnects can form a thin layer that is susceptible to charring.

The removal of these residues under the die require cleaning agents that lower surface tension and closely matched to the residue plus mechanical forces to enable the flux residue to dissolve into the cleaning agent. This force of attraction depends upon the nature of the cleaning agent and the nature of the flux residue. Penetrating low clearance gaps requires a cleaning agent that matches up with the flux residue, along with impinging forces that can deliver the cleaning agent to the residue.

On soft residues, such as the water soluble soils, flux residues are much easier to clean under low gap components. Penetrating the residue and creating a flow channel occurs rapidly. Due to the high number of I/O and low clearance gaps, selecting a residue that readily dissolves in water based cleaning agents is highly recommended. For hard no-clean flux residues, the time to clean all residues under the component gap can be five to ten times greater than the time required for a soft residue.

Cleaning Agent

The critical differentiator for removing flux residues is the cleaning agent. The ideal cleaning agent is formulated with the greenest environmental properties within performance limitations; rapidly dissolves polar protic, dipolar aprotic and non-polar soils; and is easily rinsed leaving an ionic cleaned assembly. Since flux residues are a composition of oxygen barriers, activators, rheological additives and reacted ionic salt forms, the cleaning agent requires a composition of materials that remove polar protic soils, dipolar aprotic soils, and non-polar solutes.

The cleaning agent selection should be based on the nature of the soil and cleaning equipment. Solubility of the residue into the cleaning agent is becoming a bigger issue as industry moves to lead-free and hotter reflow conditions. Selection of a paste flux that withstands peak reflow temperatures and leaves a soft residue is critical for achieving consistent cleaning.

Cleaning agents can be engineered with materials that target ionic, polar covalent and non-polar covalent materials found in the flux residue. In order to classify the materials that make up the cleaning agent, the concept of "like dissolves like" guides the formulators understanding of the forces needed to enable the flux residue to dissolve in the cleaning agent.

Research into many of the lead-free flux residue properties indicate a much broader range of oxygen barriers (resins/polymers) used over what was previously applied to tin-lead solder paste formulations. With different solder paste suppliers using a wide range of these materials, the attraction of the cleaning agent for the soils will be different. With this increased level of complexity, there will be a greater requirement for matching the cleaning agent to the soil.

The challenge in designing cleaning agents for lead-free soils is that residue properties are very different amongst solder material companies. Depending on the properties of the residue, some cleaning agent designs must drive with stronger forces than needed for soft residues. Upstream factors can change cleaning properties. As a result, there is "rarely" one best cleaning agent since the nature of today's cleaning process is far more inconsistent than years past.

Cleaning Equipment

With lower component heights, the cleaning equipment must deliver the cleaning agent to the flux residue. To remove residues under the die, the cleaning solution must wet, dissolve, create a flow channel and move all residues from under the die surface. The selection of both the cleaning agent and cleaning equipment are critical in cleaning flux residues under component gaps on leadless components.

To remove flux residues under component gaps on leadless components, cleaning equipment designs that deliver the cleaning agent to the source of the flux residue using spray-in-air are commonly used. Typical spray-in-air cleaning machines are equipped with spray nozzles that hit the board surface and then deflect to move the cleaning agent to the residue. To improve deflective energy, tighter spray nozzles deliver cleaning agents at higher pressures and fluid flows, which provide higher impact forces with less pressure drop. Once the spray hits the board surface, the deflective energy forces the cleaning agent under the component gap.

The problem with this approach is that the position of the board to the spray patterns is commonly not consistent over the board's surface. As such, some components are cleaned while others components on the same board still have flux residue remaining under the leadless component. To improve this condition, some cleaning machine companies are angling the spray nozzles so they hit the board at the leading edge of the component (Figure 7). Spray patterns that hit at the edge of the component are not as susceptible to energy losses and provide improved consistency for removing residues under leadless components.

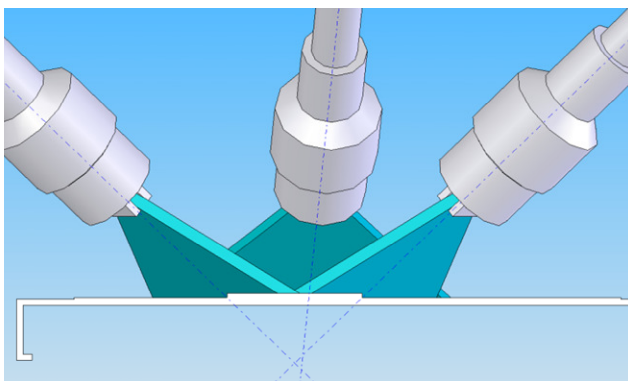

Figure 7: Angled Spray Nozzles hit at Edge of Component

To illustrate, consider a 10x10 mm μBGA with 0.4mm Pitch (Figure 8).

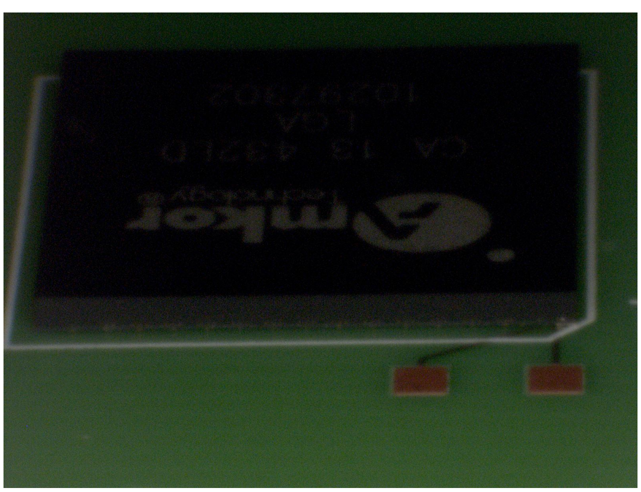

Figure 8: Area Array μBGA

Figure 9 illustrates a μBGA with 0.40 mm pitch cleaned with a spray pattern using deflective spray-in-air energy. Flux residue remained under the device.

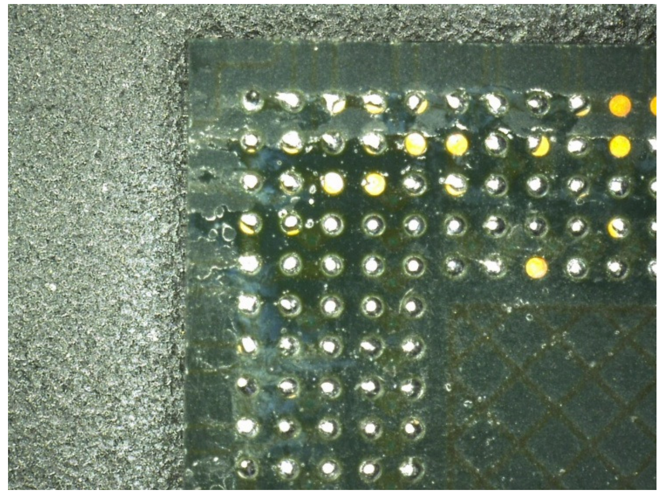

Figure 9: Flux Residues under μBGA Post Cleaning

Figure 9 illustrates the same μBGA cleaned with angled patterns using spray-in-air energy. No flux residue remained under the device.

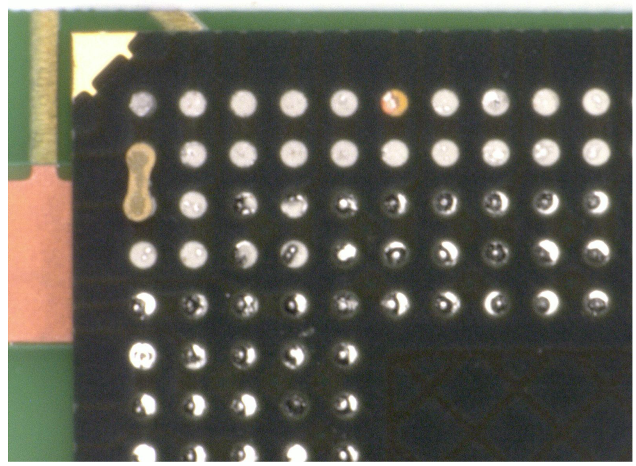

Figure 10: No Flux Residues under μBGA Post Cleaning

With gap heights less than 2 mils and tightly pitch interconnects, cleaning energy must be optimized to achieve cleaning consistency.

Summary of 5-Cleaning Forces

Variability in the five cleaning forces impacts cleaning consistency. Understanding the five cleaning forces and how they apply to a particular cleaning process differentiates a process that meets the cleaning objective versus one that fails to meet the process objective.

Each of the 5-forces are multi-faceted and must be studied to understand their influence on cleaning the flux residue from under leadless components and then integrated to achieve process consistency. Failure to consider each of the 5-forces when designing the cleaning process often leads to a poor cleaning process.

Methodology

The full factorial designed experiment allows for the simultaneous study of lead-free flux residue cleaning effects on wash time, cleaning agent, and spray impingement for removing visual flux residue under bottom termination components. When performing this experiment, the levels of all factors were varied simultaneously in an effort to study the interactions between the factors. The combinations of factor levels represent the conditions at which responses were measured. Each experimental condition and the response measurement were observed. The experimental design measured responses at all combinations of the factor levels. The design compares cleaning efficacy on 9-lead-free water soluble flux residues. Main effect plots were generated to visualize the effect of the factors on the response and to compare the relative strength of the effects.

Test Matrix – Full Factorial Designed Experiment

- 9 – Cleaning chemistries (DI water & DI w/ Defoamer)
- 3 – Belt speeds (wash times) – 1, 2 & 3 ft/min
- 4 – Spray manifold configurations
- 9 – Water soluble PbF solder fluxes
- Measured response - % of flux residue under BTC

Data Findings

The main effects plot provides a visual comparison of the factors for cleaning lead-free water soluble flux residues left under bottom termination components. The factors studied were the mean percent flux residue removed, throughput time in the inline spray-in-air cleaning machine at 1, 2, & 3 feet per minute, and spray manifold design. The effects show the overall mean for all the data, which represents 108 sites for each component type. The factors displayed represent the main effect plots that are significant according to the analysis of variance (ANOVA). A main effect is present when the change in the mean response across the levels or a factor is significant. By comparing the slopes of the lines, you can compare the relative magnitude of the process variable effects.

DI Water Only

The first data set draws a visual comparison of the effectiveness of DI water only for cleaning the nine lead-free water soluble flux residues under the low clearance components (Figure 11).

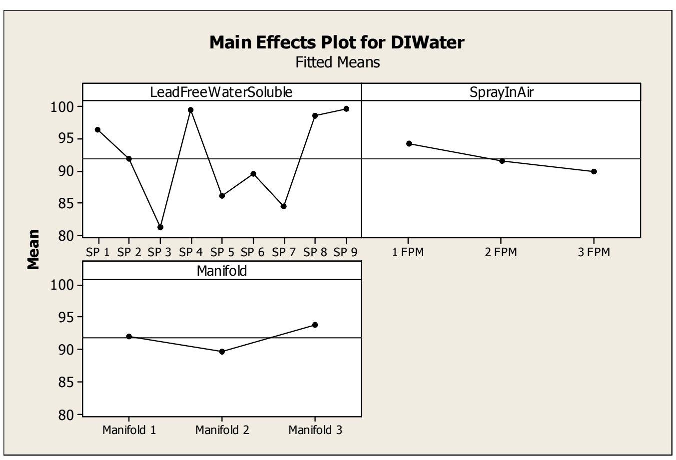

Figure 11: Main Effects Plot for DI Water Only

Water soluble flux residues are hydroscopic and active. Literature is rich with relevant research that conclusively finds circuit failures when leaving behind active water soluble flux residues under components. Water soluble flux technology needed to support lead-free circuit assemblies differ from eutectic tin-lead solder systems. Factors such as high soldering temperature and flux burn-off create pockets of harden residue that may no longer be removed with DI water only. Water with an additive may be needed to remove lead-free water soluble fluxes.

From the nine water soluble lead-free solder pastes in this study, DI water showed good performance on only two of the nine solder pastes. Flux burn-off is a common issue next to the solder joint. The data findings indicate that water with an additive may be needed.

Two other significant factors were found. Numerous research studies over the past five years indicate that high fluid flow and pressure at the surface of the assembly improve cleaning results. Four spray manifolds were tested.

1. Manifold 1 delivered the wash fluid using fan jets
2. Manifold 2 delivered the wash fluid using fan jets combined with the hurricane type water knife.
3. Manifold 3 delivered the wash fluid using coherent and fan jets.
4. Manifold 4 delivered the wash fluid using coherent jets.

For DI water only, manifold 4 was not tested due to foaming in the wash tank. The coherent jets showed a slight cleaning improvement.

The third factor tested was throughput rate. Past research studies indicate that longer wash times are needed to removed flux residues under low clearance components. The data finds slower belt speeds improve the mean percent flux removed under low clearance components.

DI Water with Defoamer

Lead-free water soluble flux residues create a foaming condition. To address this issue, a de-foaming agent was added to DI water. The main effects plot in Figure 12 compares the relative strength of the significant factors.

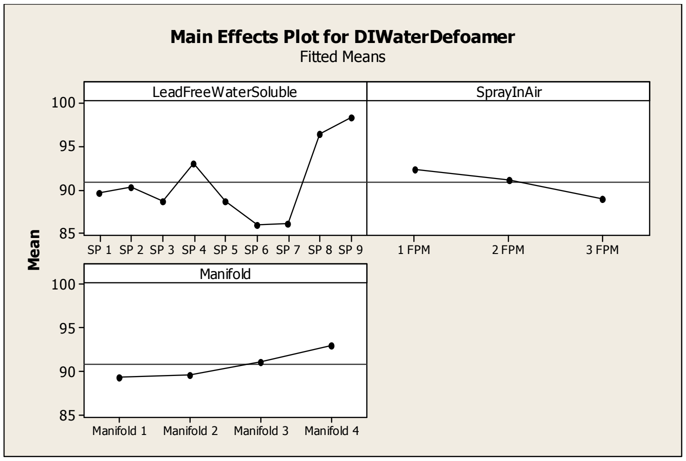

Figure 12: Main Effects Plot for DI-Water with Defoamer

High impingement spray-in-air cleaning machines turn the wash tank over an average of 2 times per minute and shear the wash fluid. The pressure from this shearing effect creates microscopic bubbles within the body of the wash tank. The foam eventually reaches the pump intake. When this occurs, there will be both the loss of pressure and foam build. Eventually this condition drops the low level sensor and shuts the machine down.

Lead-Free water soluble flux residues often create a foam condition in the wash tank. Very small levels of these residues create this condition. To address this issue, DI water with the addition of an antifoam agent was tested. The data finds water with a defoamer to be slightly less effective than DI water only. Only one of the water soluble solder pastes showed promised for removing all residues under low clearance components when using water with a defoamer.

Consistent with DI water data findings, longer time in the wash section improved cleaning results under low clearance components. Additionally, the coherent nozzle design with higher fluid flow improved cleaning.

Cleaning Agent 1

Seven engineered cleaning agents were placed into the matrix. The cleaning agents were used at 5% cleaning agent and 95% DI water. The building blocks used to engineer aqueous cleaning agents are solvency to dissolve non-polar resin structures, activators to buffer and saponify soils, wetting agents to lower surface tension, and non-reactive additives to control foam and increase the immunity region on metal alloys.

Cleaning agent 1 is an aqueous concentrated cleaning agent designed to improve wetting and lower surface tension. Cleaning agent 1 is a low foam formulation and highly effective at controlling foam build in the wash tank.

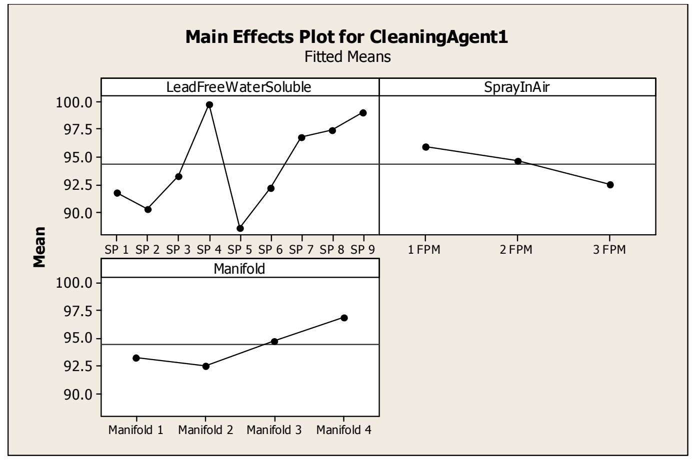

Figure 13: Main Effects Plot for Cleaning Agent 1

The main effects plot finds a slight improvement over DI water. Consistent with DI water testing, solder pastes 4, 8, and 9 were easier to clean. The data also finds that longer exposure time in the wash improves cleaning results. Additionally, higher fluid flow and coherent nozzle designs improved cleaning under low clearance components.

Cleaning Agent 2

Cleaning agent 2 is an aqueous concentrated cleaning agent built with solvency, low reactivity, and surfactancy to improve wetting, lower surface tension, and remove ionic soils (Figure 14).

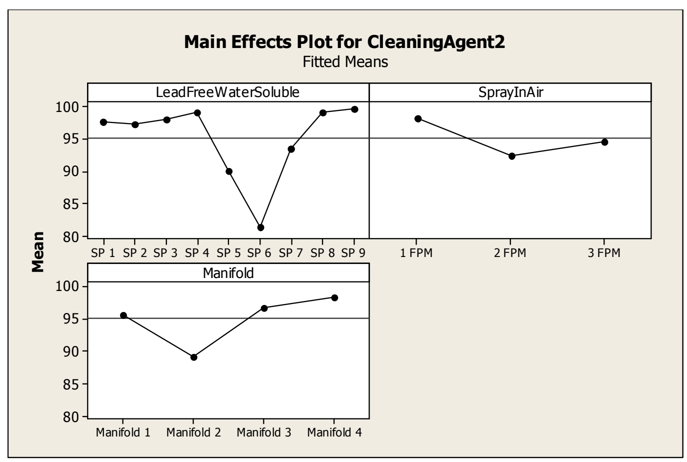

Figure 14: Main Effects Plot for Cleaning Agent 2

The data finds much improved cleaning over DI Water only. Solder paste 6 did not match well with cleaning agent 2. The data point indicates the importance of matching the cleaning agent to the soil. Longer exposure time improves cleaning but the fall off was not as significant at those for DI water. Increased fluid flow and impinging force at the board surface improved cleaning effects.

Cleaning Agent 3

Cleaning agent 3 is an aqueous concentrated cleaning agent designed to saponify flux residues. Cleaning agent 3 contains non-reactive ingredients to lower surface tension, wet, de-foam, and remove ionic soils (Figure 15). The data findings show improved results over DI water but not as good as Cleaning Agent 2. The cleaning rate was similar at one and two feet per minute but fell off at three feet per minute. High fluid flow and pressure at the board improved cleaning performance.

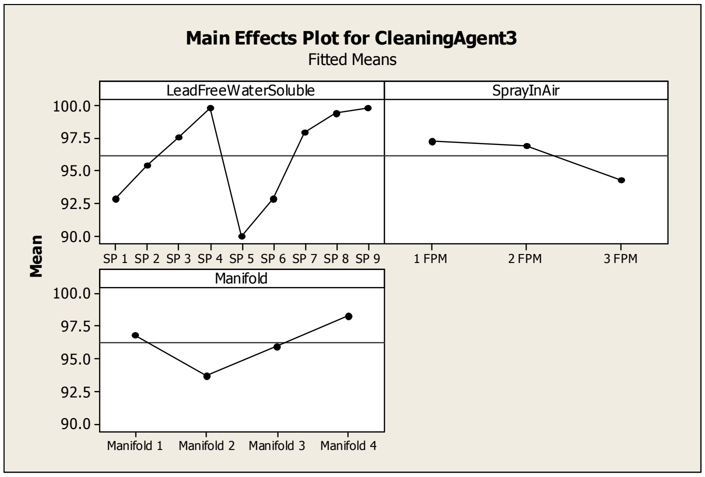

Figure 15: Mean Effect Plot for Cleaning Agent 3

Cleaning Agent 4
Cleaning agent 4 is an aqueous concentrated cleaning agent also designed to saponify flux residues. Cleaning agent 4 contains non- reactive ingredients to lower surface tension, wet, de-foam, and remove ionic soils (Figure 16). The data continues to point to the power of cleaning agent matching up to the flux residue. In this case, solder pastes 3, 8, and 9 cleaned very well even at three feet per minute.

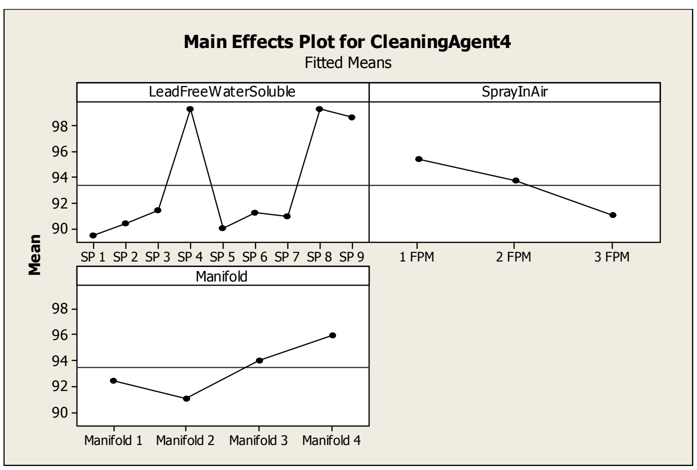

Figure 16: Main Effects Plot for Cleaning Agent 4

Cleaning Agent 5
Cleaning agent 5 is an aqueous concentrated cleaning agent designed to solvate and saponify flux residues. Cleaning agent 5 contains non reactive ingredients to lower surface tension, wet, defoam, and remove ionic soils (Figure 17). Solder pastes 4, 8, and 9 show a strong tendency to clean well with cleaning agents engineered with reactive agents.

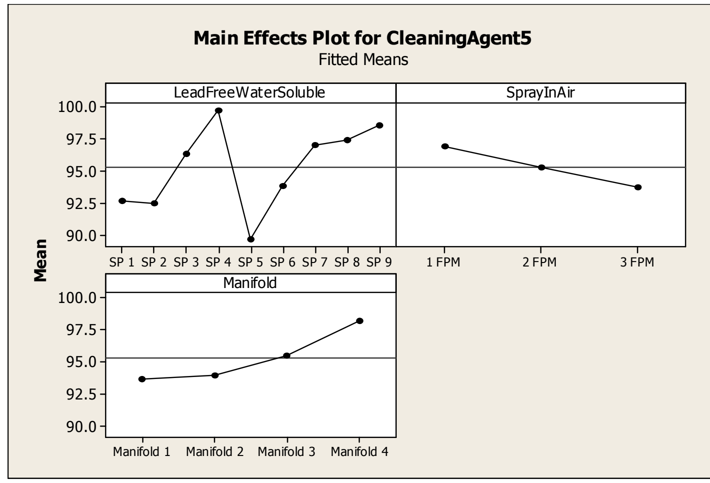

Figure 17: Main Effects Plot for Cleaning Agent 5

Cleaning Agent 6
Cleaning agent 6 is an aqueous concentrated cleaning agent designed to solvate, dissolve and saponify flux residues. Cleaning agent 6 contains non-reactive ingredients to lower surface tension, wet, de-foam, and remove ionic soils (Figure 18). Cleaning agent 6 also shows a strong match for solder pastes 4, 8 and 9.

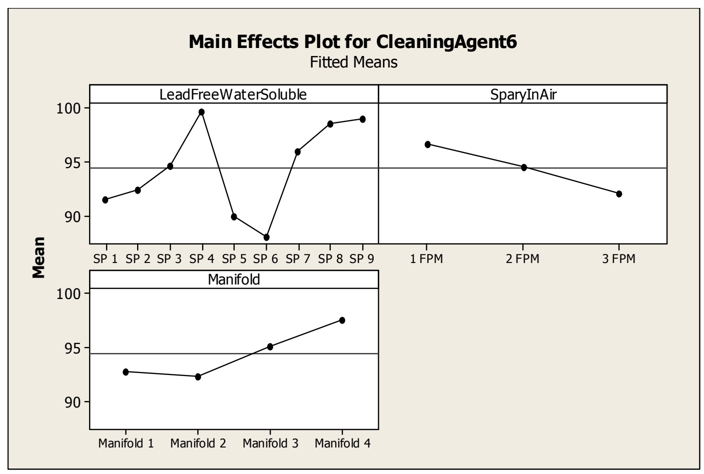

Figure 18: Main Effects Plot for Cleaning Agent 6

Cleaning Agent 7
Cleaning agent 7 is engineered as a neutral aqueous cleaning agent that drives with solvency and surfactancy. Cleaning agent 7 contains non-reactive ingredients to lower surface tension, wet, de-foam, and remove ionic soils (Figure 19). Similar to the other cleaning agents tested, cleaning agent 7 shows a strong match for solder pastes 4, 8, and 9.

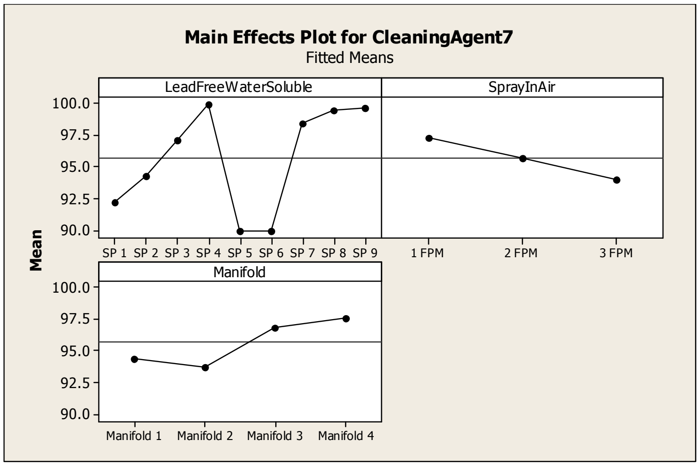

Figure 19: Main Effects Plot for Cleaning Agent 7

Inferences from the Data

The points on the main effect plots are the means of the response variable (% clean under bottom termination components) at the various levels of each factor. The reference line is drawn as the grand mean of the response data. The main effect plots compare magnitudes of main effects. The worksheet was set up with one column for the response variable and one column for each factor. Each row in the response and factor columns represents one observation.

The data infers four key findings:

1. Lead-free water soluble flux residues may require water with an additive to remove all flux residues under low clearance components. Several research studies report the need for additives to be added to DI water when cleaning lead-free water soluble flux residues. The data findings from this study support this premise.

2. A wider processing window occurs when the cleaning agent is closely matched to the flux residue. Lead-free solder pastes 1, 2, 3, 5, 6, and 7 were harder to clean and did match up as well to many of the cleaning agents tested as did solder pastes 4, 8, and 9. Cleaning agent 2 was a strong match for solder pastes 1, 2, 3, 4, 8 and 9 but was similar to the other cleaning agents on solder pastes 5, 6, and 7. Matching the solubility parameters of the cleaning agent with the flux residue is critical to opening the process window.

3. Four spray manifolds were studied. The differences were not dramatic but significant. Spray manifold 4 improved cleaning results. The manifold design delivered high fluid flow and pressure at the board surface. The data findings infer that this manifold design improves the cleaning result under low clearance components.

4. The data findings infer that time in the wash section improves cleaning under low clearance parts. Cleaning agent 2 was one exception that stood out from the data findings. When the cleaning agent is closely matched to the cleaning agent, time is not as significant of a factor.

Conclusion

Cleaning flux residues post soldering has been a high reliability criterion practiced by assemblers of military, aerospace, automotive medical devices and other value offerings. Advance package designs reduce component spacing and standoff heights. The complexity of removing flux residue increase as standoff heights reduce. Additionally, lead-free soldering appears to harden flux residues due to higher processing temperatures and flux burn off. The purpose of this research was to test the cleaning parameters needed to remove lead-free water soluble flux residues from under low clearance lead-free components.

When cleaning water soluble flux residues under low clearance components, the data findings indicate that DI water only fails to remove all flux residues. Cleaning agents closely matched to the flux residue improve cleaning results when used at low levels in DI water. With the wide range of soldering materials offered to industry, the data strongly suggests that cleaning agent differentiation comes from knowing how the cleaning agent matches up to the flux soil. This finding is critical when there is a need to remove flux residue under low clearance components. Cleaning agents closely matched to the flux soil allow for higher throughput rates.

The spray impingement manifold design was also a significant factor when cleaning all flux residues under low clearance components. Literature suggests that high flow, impingement pressure and directional forces improve cleaning under low clearance components. The data findings are consistent with these findings.

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