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Cleaning Today's Assemblies in Batch Systems

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ABSTRACT
Batch cleaning of electronic assemblies is popular in all regions of the world and continues to grow due to its flexibility, ease-of-use and economic considerations. Batch spray-in-air processes tend to dominate the new systems being installed in North America while batch immersion with and without ultrasonics are popular in Asia. In Europe, batch vapor degreasing and co-solvent processes remain quite popular. Regional preferences, local environmental regulations, economics and availability are some of the factors influencing process choice. This study was undertaken to compare the relative performance of each of these processes in cleaning flux residues from underneath low stand-off components. Pros and cons of each of these processes are highlighted.

INTRODUCTION
Cleaning today's electronics assemblies has become increasingly complex due to miniaturization, implementation of lead-free solders and high reliability standards in the newer generation of consumer and industrial electronic products. The continuously changing myriad of global environmental and safety regulations have made the task of cleaning even more challenging.

In-line aqueous spray-in-air cleaning has been popular in many regions because of its ability to clean wide range contaminants and the advantages of high through-put, aggressive mechanical agitation, and low environmental impact of the aqueous cleaners used in these systems. However, for manufacturers with low throughput operations, the cost and footprint requirements of this type of equipment are difficult to justify.

Batch cleaning processes have become increasingly popular around the world in the last few years because of their lower cost and footprint requirements, and to their flexibility in operation. Batch systems have been effective in cleaning Sn/Pb solders; but these systems are being challenged with the push towards lead-free systems in today's assembly manufacturing. While batch systems have been available for decades, there has been little information on the comparative effectiveness of the various types of equipment in removing flux residues. This study was undertaken to fill this gap. The objectives of this study are 1) to evaluate the cleaning effectiveness of various batch processes in removing flux residues from underneath low stand-off components as compared to an inline aqueous spray-in-air process; and 2) to determine if there is a difference in the effectiveness of these individual cleaning processes on Sn/Pb and Pb-free solder paste residues.

BACKGROUND
Batch cleaning equipment can broadly be classified into four categories:

1) Batch Spray-in-Air Systems
2) Batch Immersion/Ultrasonic Systems
3) Batch Vapor Degreasing Systems
4) Batch Co-Solvent Vapor Degreasing Systems

Other less widely used batch systems include Batch Spray-under-Immersion Systems and Batch Centrifugal Systems and are not included in this study.

Batch Spray-in-Air Systems
Batch spray-in-air systems are typically referred to as batch dishwashers due to their resemblance to household dishwashers. The major advantages of these types of systems are their small footprint, low purchase cost, low energy and material requirements, and ease-of-use. These systems can be single-chamber or multi-chamber units, though the former are more widely used. The units operate through the use of rotating spray bars which spray the cleaning solution over the boards which are held in racks. The complete cleaning cycle is typically an optional prewash followed by a wash and multiple rinse cycles. The cleaning agent can either be reused or disposed of after a single cycle. Because the process has to go through a complete cycle of wash, rinse and dry before the next cycle can begin, the throughput rate is low in these systems. Typical batch spray-in-air systems are designed for aqueous cleaning since these systems utilizing solvents need to be explosion-proof and have appropriately rated electrical systems.

Batch Immersion/Ultrasonic Systems

Batch immersion/ultrasonic systems can either run solvent-based or aqueous-based cleaning chemistries. These systems have multiple tanks for washing and rinsing steps. While the footprint is larger than a dishwasher, they are relatively inexpensive, have low energy requirements, and have higher throughput. Cleaning and rinsing are performed with the boards immersed in the cleaner and may utilize ultrasonic agitation. Process temperatures for both systems (with and without ultrasonics) are usually set 30ºF below the flash points of the cleaning materials in order to avoid other fire prevention controls. After the wash tank, parts are typically moved through multiple rinse tanks and are finally dried. Solvent based systems are rinsed with either solvent or water, while aqueous based systems use water for the rinse steps. The use of ultrasonics for electronics cleaning was a concern in the past, but has found acceptance in recent years as the probability of damage to electronic components is minimal in the newer generation of high-frequency (40 KHz and higher) units with sweep capability.

Batch Monosolvent Vapor Degreasing Systems

A conventional vapor degreasing system is equipped with either one or more sumps and uses a single solvent, referred to as monosolvent, both as a washing and rinsing agent. A typical vapor degreasing monosolvent is a low boiling, high vapor pressure, non-flammable material that is either a single component or an azeotrope. As the monosolvent boils, it forms a blanket of vapor which is contained within the equipment by cooling coils near the top of the equipment opening. In a one sump degreaser, the part to be cleaned is typically immersed in the vapor phase; the cleaner condenses on the part, cleaning it and carrying the soil away. In a two sump vapor degreasing process, the part to be cleaned may be first submerged in the boiling sump to loosen very tough soils. The part may then be (or initially) submerged into the rinse sump, which is constantly being filled with clean monosolvent that is being condensed on the cooling coils. The rinse sump continually overflows into the wash sump. The part is then raised into the vapor space where the vapor condenses on the part which acts as the final rinse. In this process, contaminants are concentrated in the wash sump. Being a non-aqueous process, vapor degreasing is especially useful in cleaning water-sensitive assemblies.

Batch Co-solvent Vapor Degreasing Systems

The co-solvent vapor degreasing process is similar to a conventional vapor degreasing process and requires a two sump vapor degreaser. The process involves the use of a high boiling solvent blend or Solvating Agent (SA) that is mixed with a low boiling, high vapor pressure, non-flammable solvent or Rinse Agent (RA). The boil sump consists of both the SA and the RA, while the rinse sump consists exclusively of RA. The operating temperature of the boil sump is controlled by the ratio of the SA to the RA. The RA boils in the boil sump thereby creating a vapor blanket. Cleaning only takes place in the boiling sump so the parts to be cleaned must be lowered into the boil sump to remove the soil. The parts are then immersed in the rinse sump to remove the dissolved soil and the SA, and then raised into the vapor space where the RA condenses on the parts for a final rinse.

The co-solvent process offers several advantages over other cleaning/defluxing processes. Typical SAs used in the co-solvent process are environmentally friendly, non-hazardous materials that are designed to remove a wide range of flux residues. SAs typically have higher soil-loading capabilities than conventional monosolvents, thus reducing the need for frequent solvent change-outs. The available RAs are also environmentally friendly, non-hazardous materials with fast-drying capability. The co-solvent process offers the advantage of greater flexibility in cleaning temperature and higher solvency compared to the monosolvent process and thus is more suited for removing stubborn flux residues.

EXPERIMENTAL PROCEDURE

A variety of popular solder pastes, both Sn/Pb and Pb-free, were used in determining the cleaning ability by each process. The pastes are listed below in Table 1. A majority of the solder pastes selected were "no-clean" solder pastes as they are typically more difficult to clean than other types. Water-soluble (WS) and Rosin Mildly Activated (RMA) solder pastes were also included.

Specially designed FR-4 test boards were populated with 0603 chip capacitors with a typical stand-off height of 1 mil. The test boards were reflowed in an air atmosphere at the manufacturer specified reflow profile for each solder paste. In each process the reflowed boards were allowed to sit for 24 hours before cleaning to simulate the worst-case scenario. After cleaning, the boards were evaluated for any remaining residues. Evaluation was done by removing the 0603 chip capacitors from the board and viewing the areas under those components at 50X magnification using a HIROX digital microscope. Depending on the amount of residue around all solder joints on the board and underneath the 0603 components, the boards were rated for cleanliness as "Clean", "Partially Clean" and "Not Clean". Figures 1-2 show the pictures of flux residue around and underneath the 0603 chip capacitor on the test board prior to cleaning. Figures 3-5 illustrate the various grades of cleanliness.

Table 1. Solder pastes tested

Solder Paste Manufacturer	Solder Paste	Sn/Pb or Pb-free	Alloy	Flux Type	J-STD-004 Flux Classification
Aim	NC 254 SAC305	Pb-free	SAC 305	NC	REL0
Cookson	Alpha RMA 390 DH3	Sn/Pb	Sn63/Pb37	RMA	ROL0
Cookson	Alpha OM 338-T	Pb-free	SAC 305	NC	ROL0
Heraeus	F640 SA30C5-89M	Pb-free	SAC 305	NC	ROL0
Indium	SMQ92J	Sn/Pb	Sn63/Pb37	NC	ROL0
Indium	3.1	Pb-free	SAC 305	WS	ORM1
Indium	5.1 AT	Pb-free	SAC 305	NC	ROL1
Kester	Easy Profile 256	Sn/Pb	Sn63/Pb37	NC	ROL0
Kester	EnviroMark 907	Pb-free	SAC 305	NC	ROL0
Senju	Ecosolder M705-GRN-360-K2-V	Pb-free	SAC 305	NC	ROL0

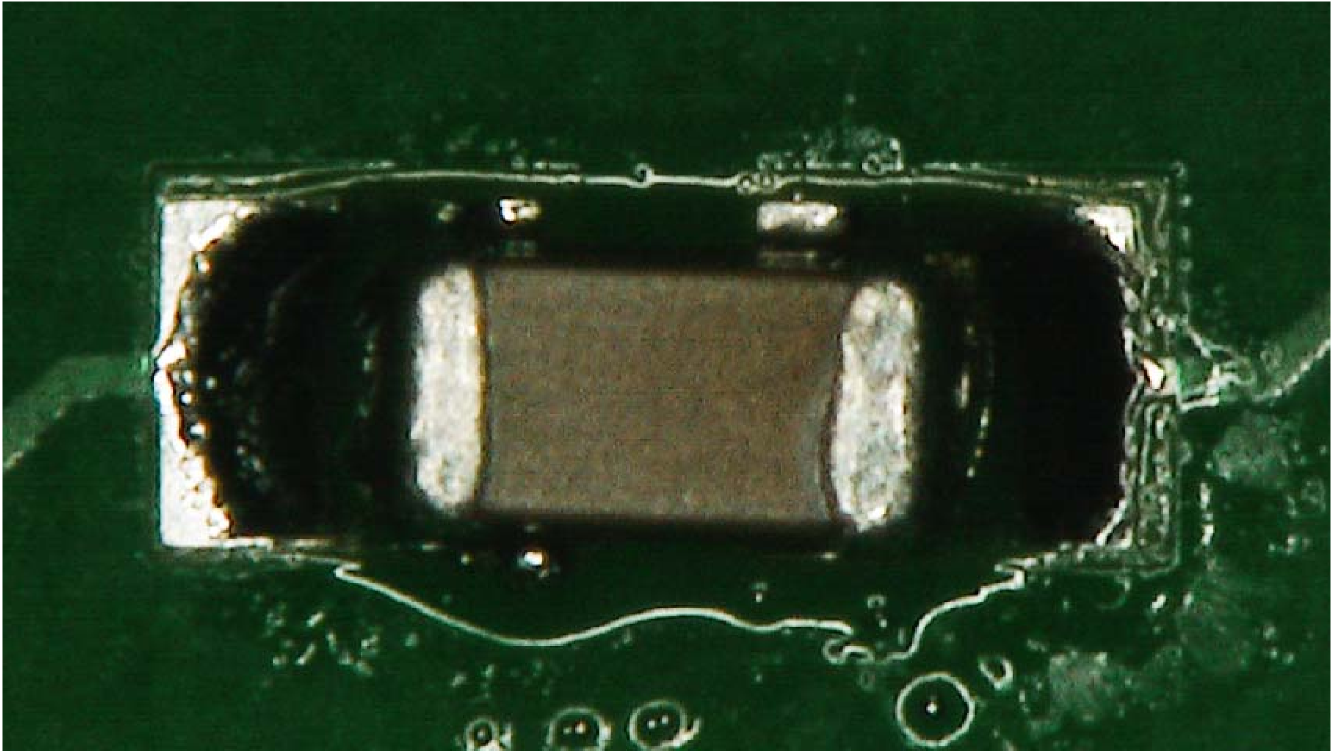

Figure 1. Flux residue around 0603 chip capacitor prior to cleaning

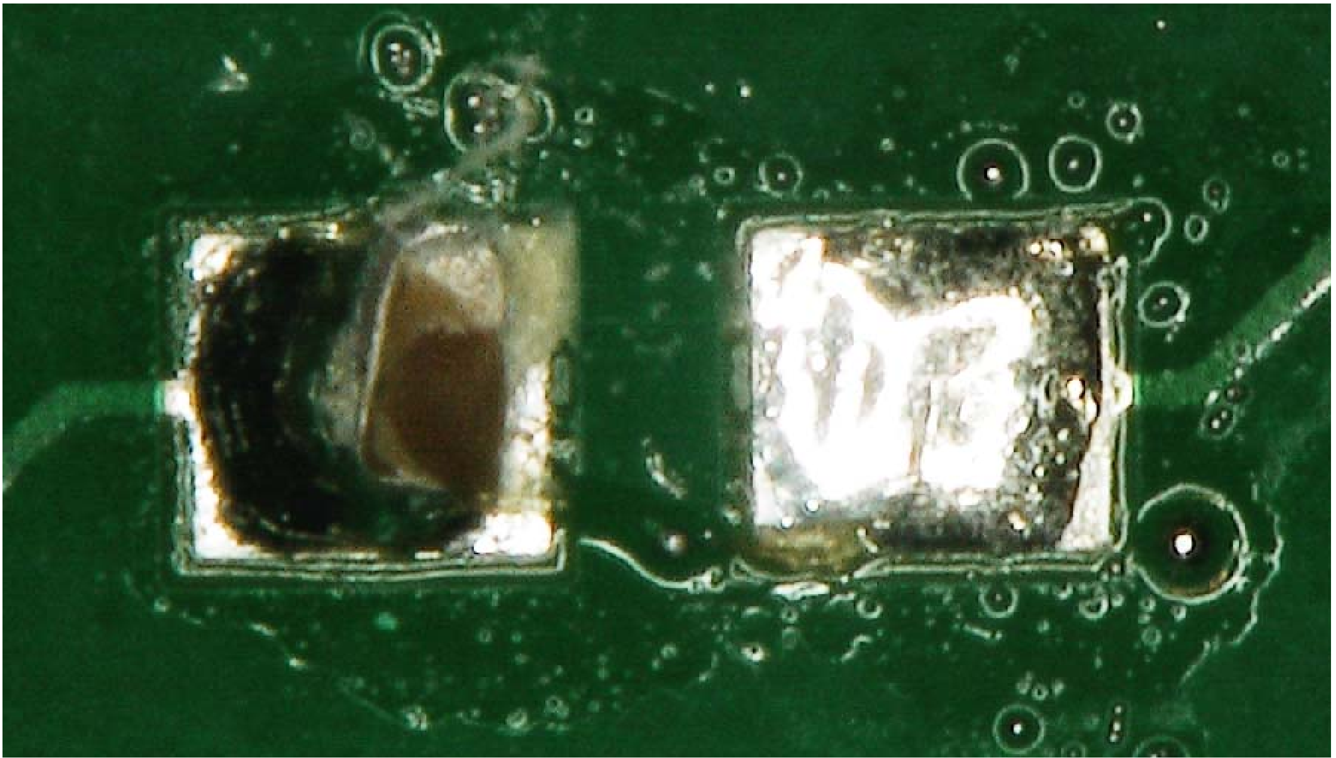

Figure 2. Flux residue underneath 0603 chip capacitor prior to cleaning

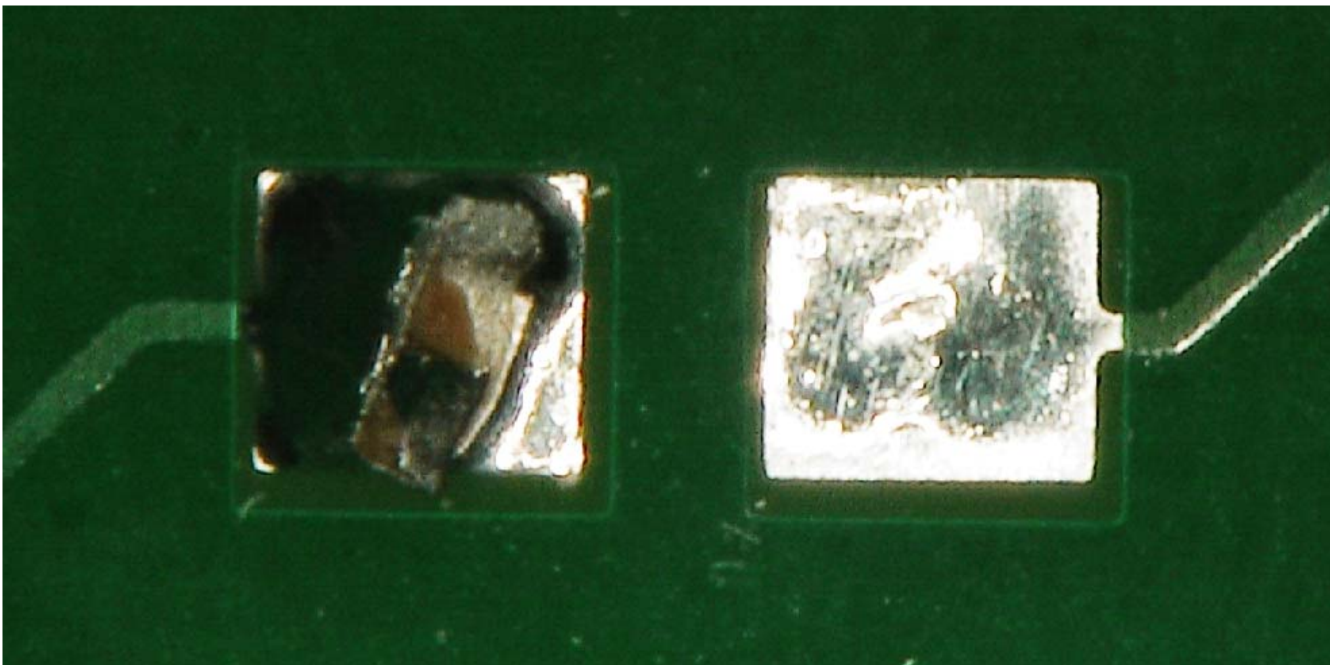

Figure 3. Boards rated as "Clean"

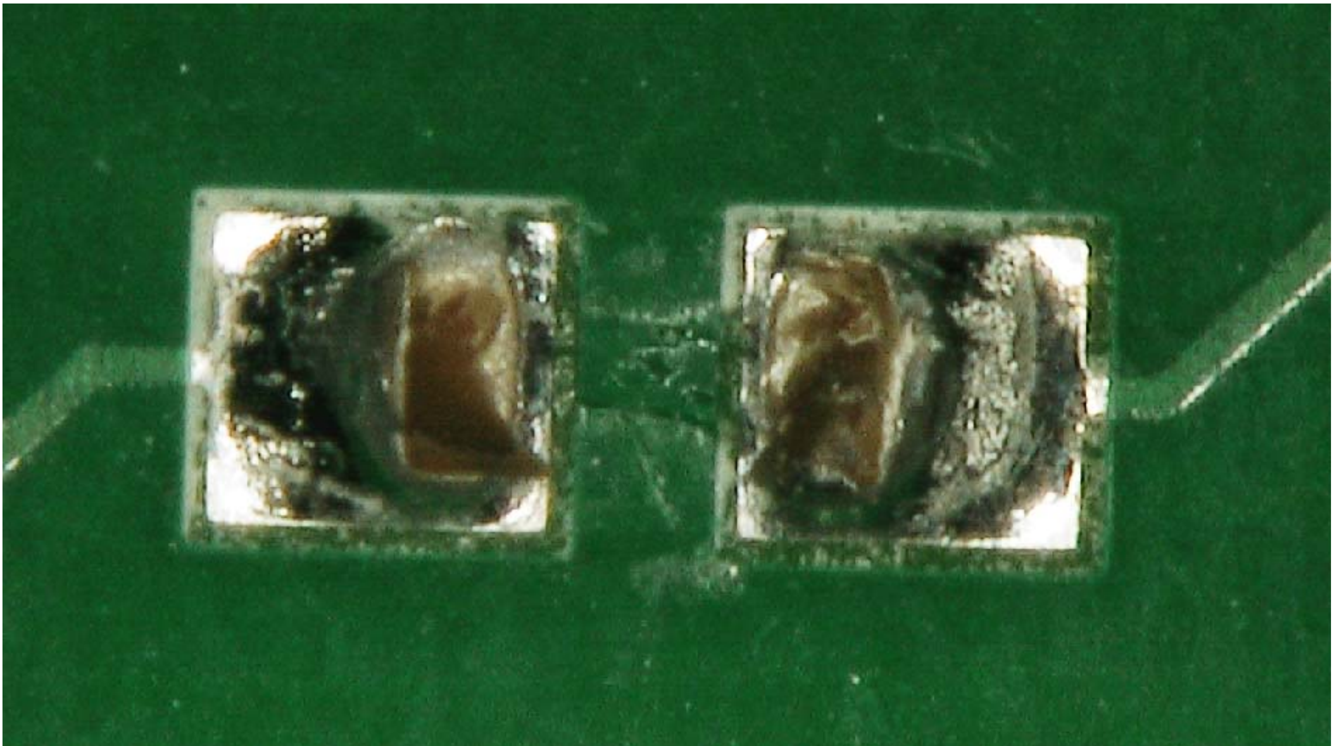

Figure 4. Boards rated as "Partially Clean"

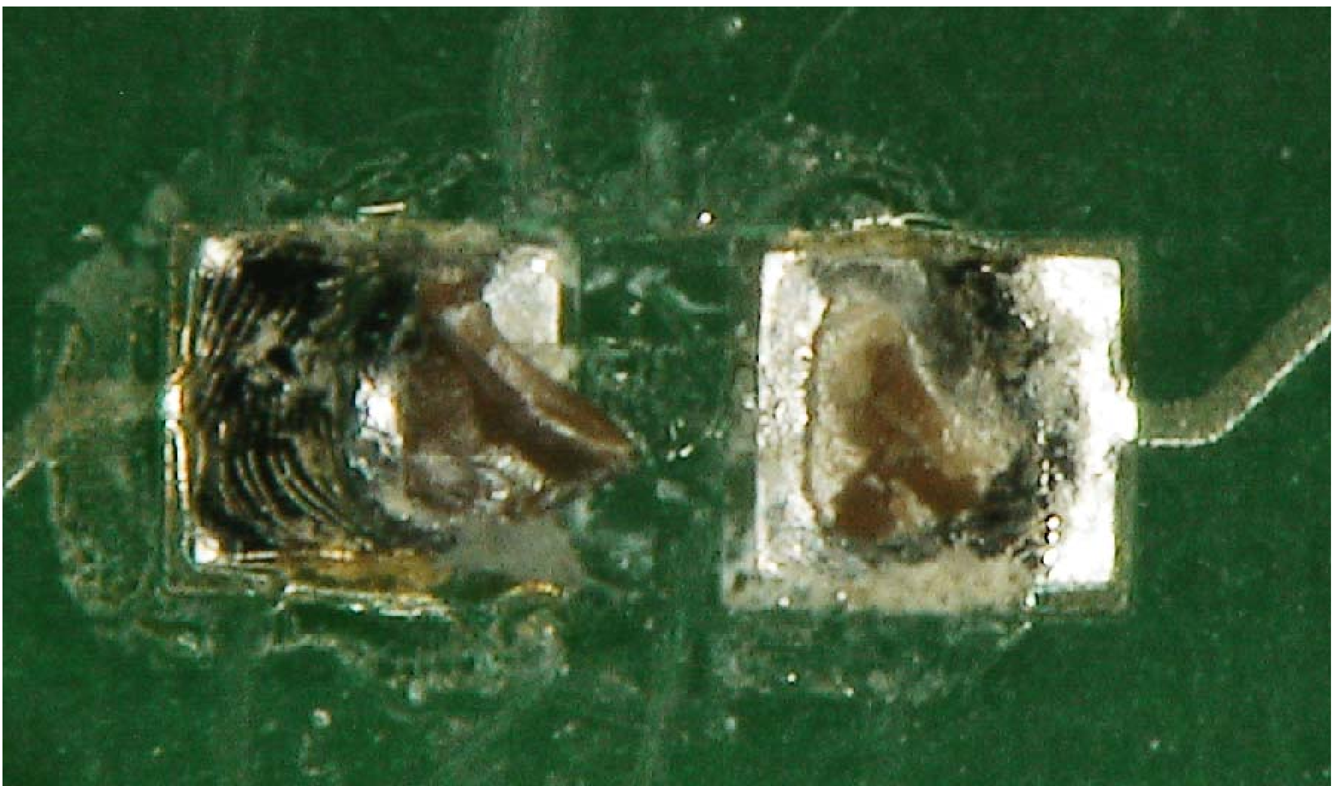

Figure 5. Boards rated as "Not Clean"

Cleaning tests were run in an inline aqueous system and the four different batch systems as listed below:

1) Inline Aqueous Spray-in-Air
2) Batch Aqueous Spray-in-Air
3) Batch Aqueous Ultrasonic
4) Batch Monosolvent Vapor Degreaser
5) Batch Co-solvent Vapor Degreaser

Aqueous cleaning chemicals were used in the spray-in-air and ultrasonic systems as they are more prevalent than solvent based cleaners in these systems. The monosolvent and co-solvent vapor degreasing processes are non-aqueous processes and use organic and/or halogenated solvents. The process parameters and cleaning chemistries used in each process are described below.

Inline Aqueous Spray-in-Air

An inline spray-in-air cleaning unit equipped with prewash, wash, chemical-isolation section (chem-iso), two rinse stages and a drying section was used to conduct the tests. Operating parameters that were varied were the concentration of the wash solution and the belt speed (Table 2). The wash concentration varied from 15-20% (w/w), and the belt speed varied from 1.5-2.5 ft/min. The wash temperature was kept constant at 150ºF. The cleaning agent was sprayed on to the boards through coherent jet nozzles with an average spray pressure of 48 psi. The two DI water rinses were maintained at 140ºF and 28 psi pressure. The boards were then dried at 110ºF with forced air. The total cycle time for cleaning for each of the three tests varied between 6 and 9 minutes.

Table 2. Operating Parameters for Inline Aqueous Spray-in-Air Cleaning Tests

	Parameters Varied		Parameters Held Constant							
Test	**Belt Speed (ft/min)**	**Wash Conc (%)**	**Wash Temp (°F)**	**Wash Spray Pressure (psi)**	**Initial Rinse Temp (°F)**	**Initial Rinse Spray Pressure (psi)**	**Final Rinse Temp (°F)**	**Final Rinse Spray Pressure (psi)**	**Drying Temp (°F)**	**Total Cycle Time (min)**
1	1.5	20	150	48	140	28	140	28	110	9
2	2.5	15	150	48	140	28	140	28	110	6
3	1.5	15	150	48	140	28	140	28	110	9

The aqueous cleaner used is a new-generation defluxer which is inherently low-foaming and is a mild saponifier with a pH of less than 10.5 at use concentration. No sump-side additives were needed as the aqueous cleaner has built-in defoamers, wetting agents and corrosion inhibitors enabling the cleaner to penetrate into tight spaces and render the solder joints bright and shiny.

Batch Aqueous Spray-in-Air

A stainless steel dishwasher-style batch spray-in-air system with coherent jet nozzles at the top, middle and bottom and a high-temperature wash capacity was used for testing this process type. Three sets of test boards were run in the batch spray-in-air equipment at different operating parameters. The operating parameters that were varied were the wash concentration, wash time and wash temperature (Table 3). The wash concentration was varied from 10-25%; and the wash time was varied from 15-20 minutes. A high temperature range of 180-200ºF was chosen for the test, as previous experiments in this equipment at lower temperatures showed only marginal results. The wash cycle was followed by an initial DI water rinse at 160ºF for 10 minutes, followed by a final DI water rinse at 160ºF for 1 minute. The boards were then dried in the forced air drying cycle at 151ºF for 10 minutes. The total cleaning cycle time for each of the three tests ranged from 36 to 41 minutes.

Table 3. Operating Parameters for Batch Spray-in-Air Cleaning Tests

	Parameters Varied			Parameters Held Constant						
Test	**Wash Temp (°F)**	**Wash Conc (%)**	**Wash Time (min)**	**Initial Rinse Temp (°F)**	**Initial Rinse Time (min)**	**Final Rinse Temp (°F)**	**Final Rinse Time (min)**	**Drying Temp (°F)**	**Drying Time (min)**	**Total Cycle Time (min)**
1	180	25	15	160	10	160	1	151	10	36
2	200	20	15	160	10	160	1	151	10	36
3	200	10	20	160	10	160	1	151	10	41

The cleaning agent used is a new generation cleaner which is environmentally-safe, is inherently low-foaming, and a mild saponifier with built-in additives that do not dull solder joints even at high temperatures and prolonged contact times; conditions typically encountered in batch spray-in-air equipment. The pH of the cleaning agent is around 10.5 at use concentration.

Batch Aqueous Ultrasonic

Three sets of test boards were run in a variable-power, 40 KHz bench-top batch ultrasonic equipment with a 3 KHz sweep frequency. The watt density was 62.5 watts/gal. The operating parameters that were varied were the wash temperature and wash concentration (Table 4). The wash time was fixed at 10 minutes for each test. Following the wash, the test boards were then rinsed twice in DI water at 160ºF for 5 minutes. The test boards were then forced-air dried at 125ºF for 2 minutes. The total cycle time for each of the three tests was 22 minutes.

Table 4. Operating Parameters for Batch Ultrasonic Cleaning Tests

	Parameters Varied		Parameters Held Constant							
Test	Wash Temp (°F)	Wash Conc	Wash Time	Initial Rinse Temp (°F)	Initial Rinse Time (min)	Final Rinse Temp (°F)	Final Rinse Time (min)	Drying Temp (°F)	Drying Time (min)	Total Cycle Time (min)
1	160	25	10	160	5	160	5	125	2	22
2	160	20	10	160	5	160	5	125	2	22
3	165	15	10	160	5	160	5	125	2	22

The cleaning agent used is a free-rinsing, mild saponifier capable of good cavitation in ultrasonic equipment. The pH of the cleaning agent was less than 10.5 at use concentration. The environmentally-safe, non-dulling formula is compatible with commonly used electronic substrates and can be used in immersion applications with or without ultrasonics.

Batch Monosolvent Vapor Degreaser

A standard two-sump vapor degreaser with ultrasonics was utilized for cleaning three sets of test boards at different operating parameters. The operating parameters that were varied were the wash time and ultrasonic agitation in the rinse sump (Table 5). The time in the rinse sump and the vapor phase rinse were held constant at 10 and 1 minutes, respectively. The total cleaning cycle time varied between 21 and 31 minutes for the three tests.

The monosolvent chosen for testing was an azeotropic mixture of n-propyl bromide and isopropyl alcohol which is a common electronics vapor degreasing solvent. The boiling point of the azeotropic mixture is 154ºF. This vapor degreasing solvent has traditionally been used with rosin-based Sn/Pb solder pastes with a high rate of success.

Table 5. Operating Parameters for Batch Monosolvent Vapor Degreasing Tests

	Parameters Varied		Parameters Held Constant			
Test	Time in Boil Sump (min)	Ultrasonics	Boil Sump Temp (°F)	Time in Rinse Sump (min)	Time in Vapor Rinse (min)	Total Cycle Time
1	10	No	154	10	1	21
2	10	Yes	154	10	1	21
3	20	No	154	10	1	31

Batch Co-solvent Vapor Degreaser

A two-sump vapor degreaser was utilized to run three sets of test boards in the co-solvent vapor degreasing process at different operating parameters. The co-solvent mixture consisted of an organic SA and a fluorinated RA at various ratios. Depending on the ratio, the boiling point of the mixture varied from 155-185ºF. The operating parameters that were varied were the wash temperature (SA/RA ratio) and the wash time (Table 6). The time in the rinse sump and the vapor phase rinse were held constant at 10 and 1 minutes respectively. No ultrasonic agitation was used. The total cleaning cycle time varied between 21 and 31 minutes for the three tests.

The SA used in this study was a newly developed organic solvent mixture with increased solvency towards rosin/resin-based flux residues. The RA used was a high-boiling fluorinated solvent.

Table 6. Operating Parameters for Batch Co-solvent Vapor Degreasing Tests

Test	Parameters Varied			Parameters Held Constant		
	SA/RA Ratio	Boil Sump Temp (°F)	Time in Boil Sump (min)	Time in Rinse Sump (min)	Time in Vapor Rinse (min)	Total Cycle Time (min)
1	70/30	170	10	10	1	21
2	80/20	185	10	10	1	21
3	50/50	155	20	10	1	31

RESULTS

Cleaning Results for Inline versus Various Batch Processes

The cleaning results for various processes are listed below in Table 7. A total of ten solder pastes, that included both Sn/Pb and Pb-free, were tested in this study. The number of pastes rated as "Clean", "Partially Clean" and "Not Clean" for each process are listed in the table below. The boards rated as "Clean" had no flux residue left on all solder joints on the board and underneath the 0603 chip capacitors (Figure 3). The boards rated as "Partially Clean" had some residue left either on the solder joints or underneath the 0603 capacitor (Figure 4). A large amount of flux residue was left on the solder joints and underneath the 0603 capacitors (Figure 5) for the boards rated as "Not Clean". While some of the flux residues on the "Partially Clean" and "Not Clean" boards can be totally removed under the right operating parameters for that process, others may be limited by the cleaning chemistry or the lack of enough mechanical or thermal energy being used in that process. Optimum operating parameters for any process will depend on the type of equipment, the cleaning chemistry, substrate configuration, and the solder paste/flux residues. It is imperative to run trials to find these optimum conditions before establishing a cleaning process.

Table 7. Cleaning Results

Test	Number of Pastes Rated as		
	Clean	Partially Clean	Not Clean
Inline Aqueous Spray-in-Air			
1	10	0	0
2	7	2	1
3	8	2	0
Batch Aqueous Spray-in-Air			
1	8	2	0
2	10	0	0
3	8	2	0
Batch Aqueous Ultrasonic			
1	8	2	0
2	8	1	1
3	8	2	0
Batch Monosolvent Vapor Degreaser			
1	4	4	2
2	6	4	0
3	4	5	1
Batch Co-solvent Vapor Degreaser			
1	8	1	1
2	8	2	0
3	5	2	3

For the inline aqueous spray-in-air system used in this study, a set of optimum conditions was found where all ten solder paste residues were able to be completely cleaned. These set of optimum conditions represent the right combination of thermal, mechanical and chemical means along with the right contact time to clean the flux residues.

A set of optimum conditions were similarly found for the batch aqueous spray-in-air system used in this study where all ten solder pastes were cleaned. For the batch process, higher temperatures and longer contact times were needed to clean the residues as compared to an inline process.

For the batch aqueous ultrasonic process, for a few pastes partial residue was left underneath the components in all test conditions. While it may be possible to clean these solder pastes with further optimization of the process parameters, the lack

of high pressure spray jets to remove some of the residues from underneath the components may be a limiting factor. While spray-in-air equipment relies on higher mechanical forces to dislodge residues, an ultrasonic process relies on cavitation to remove residues. For some of these solder pastes, the cavitation energy may not be sufficient to totally clean under the components.

The results were marginal for monosolvent vapor degreasing process using n-propyl bromide/IPA azeotrope. Only six of the ten pastes were completely clean at the best operating parameters. This process is very efficient for the narrow set of pastes that it can clean, but if a wide variety of solder pastes/fluxes need to be cleaned, the process becomes limited by the solvency and the boiling point of the solvent.

A co-solvent process can be used to off-set some of the limitations of the monosolvent process observed in this study. Eight of the ten solder pastes could be cleaned by the co-solvent process even without ultrasonic agitation as compared to only six pastes by the monosolvent process with ultrasonic agitation. With the use of ultrasonic agitation and further optimization of the co-solvent process, the remaining solder pastes may likely be cleaned completely.

The co-solvent process run at the same temperature (155°F) as the monosolvent process did not show any improvement in performance. But since the co-solvent process can be run at much higher temperatures with better solvency towards newer rosin/resin based residues, a wider set of pastes could be cleaned at temperatures above 170°F.

Sn/Pb versus Pb-free

Figures 6 and 7 illustrate the percentage of pastes rated as "Clean" for each process for Sn/Pb and for Pb-free solder pastes, respectively. As observed in many previous studies, the Pb-free solder pastes were difficult to clean compared to Sn/Pb solder pastes. As shown in Figure 6, all the three aqueous processes were able to clean all the Sn/Pb solder pastes tested at most operating conditions. However, for the Pb-free solder (Figure 7), most pastes could only be cleaned at certain optimum operating parameters. The inability of the aqueous ultrasonic process to clean certain pastes indicates the need for additional mechanical forces to clean underneath components. In general, for an aqueous process, Pb-free solder required higher concentrations of the cleaning agent, higher wash temperatures and longer wash times when compared to Sn/Pb solder.

For cleaning of Sn/Pb solder by vapor degreasing processes, as shown in Figure 6, the co-solvent process showed better results than the monosolvent process due to the higher operating temperatures and better solvency characteristics offered by that process. Temperature seems to be a critical variable here as the cleaning tests run at the same temperature did not show appreciable difference between a monosolvent and co-solvent process. Therefore, due to limitations of achieving higher temperatures and solvency in a monosolvent process, a co-solvent process is preferred. For cleaning of Pb-free solder by vapor degreasing processes, as shown in Figure 7, not all solder pastes were able to be cleaned even at higher temperatures used in a co-solvent process. Use of ultrasonic agitation or a spray-wand may be needed to clean certain Pb-free solder pastes using these processes. In general, Pb-free pastes required higher operating temperatures and higher solvency cleaning agents than Sn/Pb solder.

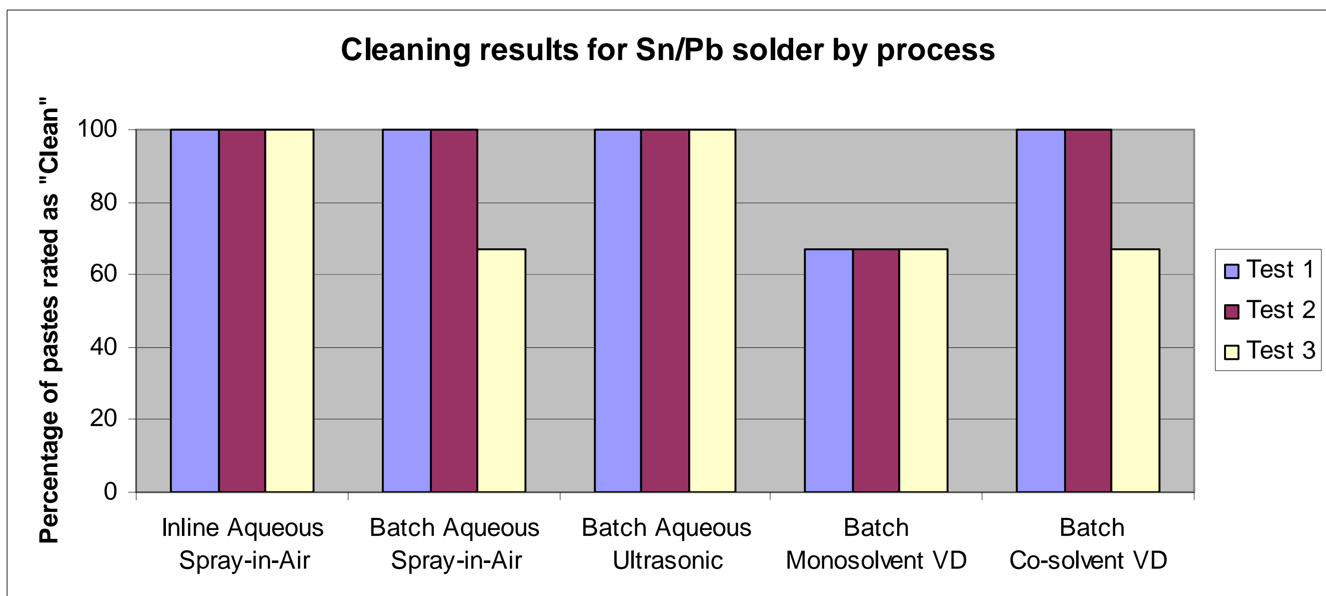

Figure 6. Sn/Pb solder cleaning results

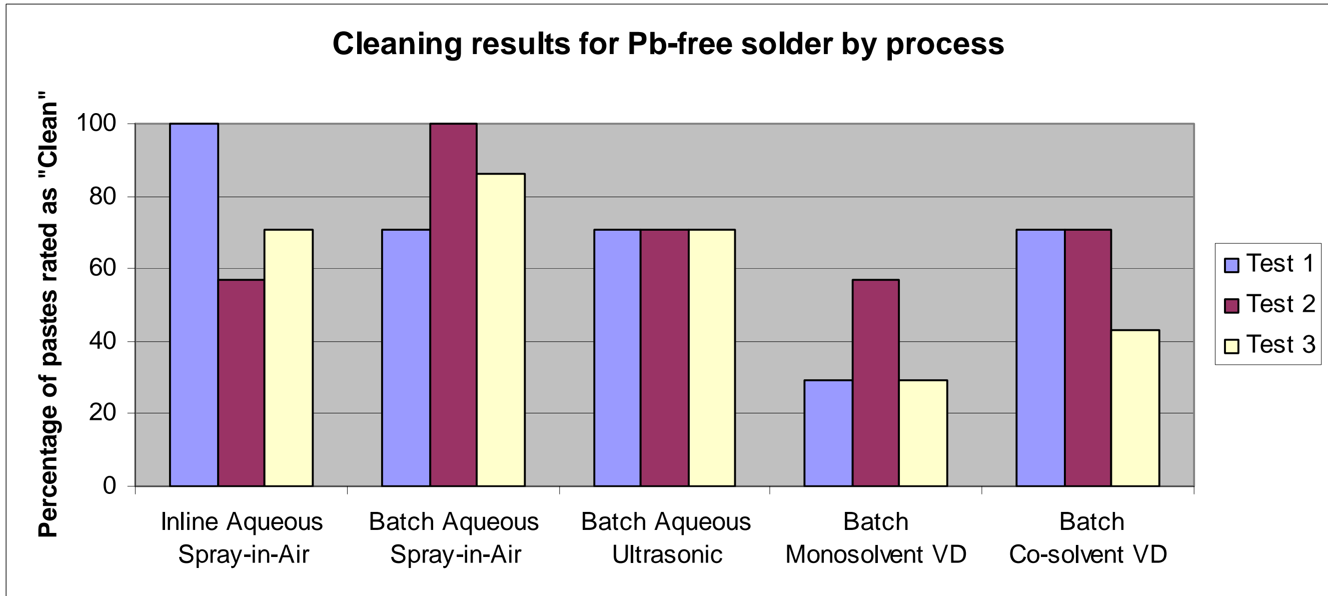

Figure 7. Pb-free solder cleaning results

Conclusions

Batch systems can be utilized to clean a majority of the flux residues, both Sn/Pb and Pb-free from underneath low-stand off components. By adjusting the operating parameters within each batch process type to optimize conditions for agitation, temperature, wash time and cleaning chemistry, results comparable to inline cleaning can be achieved. As expected, the batch monosolvent is the least aggressive cleaner with fewer operating parameters that can be varied. The batch co-solvent process adds the ability to adjust wash temperatures to some extent. The use of ultrasonics in these systems should improve performance significantly as seen in the monosolvent results. For batch spray-in-air and batch ultrasonics, the greater number of operating parameters to adjust gives these processes greater flexibility.