Optimizing cleaning energy with spray in air systems - pt 1

In Global SMT & Packaging issue 5.6 (June/July 2005), Stach & Bixenman presented research for optimizing cleaning energy in batch and inline cleaning systems. Phase II of this research, presented here, tests the process cleaning rate equation, which equals the static cleaning rate (chemical forces) plus the dynamic cleaning rate (mechanical forces), using spray-in-air cleaning equipment. The baseline for this experiment establishes the solubility rate of the cleaning solution at static conditions to determine the dissolution rate of flux residue at a pre-determined cleaning chemistry concentration and temperature. Once the cleaning rate is known, how will it be improved by applying physical energy to the board surface? The designed experiment will test the effect of energy applied to the board surface by varying pressure at the board surface. The study's hypothesis infers that a known dissolution rate and a known surface energy configuration allows an equation to calculate cleaning time and distance.

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Keywords:
Process Cleaning Rate, Cleaning, Pb-free.

Background

The objective of spray-in-air batch and in-line cleaning systems is to reduce time by engineering fluid displacement that maximizes the physical energy delivered at the surface to be cleaned. An optimized cleaning system delivers the necessary chemistry and energy to clean the most difficult and sensitive areas at a rate that will meet the process time requirements using minimal chemical energy and floor space consumption. Process savvy helps avoid common mistakes in controlling process parameters, such as time, temperature and concentration, or operator variables related to racking and shadowing in dishwasher style cleaners. Understanding the balance between static chemical and dynamic mechanical forces is fundamental in predicting and optimizing process performance at each step of the washing, rinsing and drying process.

The timing and sequence of events in a cleaning process are critical, requiring careful thought and understanding. The pre-wash should thoroughly wet the parts with the wash solution chemistry and provide sufficient flow and contact time to bring the assembly to wash temperature. This facilitates 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 and optimizes the dynamic rate by focusing the maximum physical energy at the part surfaces. The cleaning rates in in-line and planar racked batch cleaners can be significantly improved by engineering impingement systems that deliver the cleaning chemistry to the heart of the residue.

Problem statement

Today, many high reliability electronic assemblies require removal of tenacious no-clean flux residue and other residual contaminants. This is compounded by the ongoing change to Pb-free flux formulations that have their own set of cleaning problems, many of which are just not being understood. Miniaturization and reliability concerns drive more customers to specify cleaning as a required step in the manufacturing process. The problem is that cleaning performance changes when processing Pb-free, different flux types, dense substrates, and boards assembled with advanced packages. Chemical and mechanical forces must work in tandem to deliver totally cleaned assemblies on a wide range of residues, at higher reflowed temperatures, while lowering cost of ownership. This research uses a correlational quantitative design to measure mechanical fluid transfer efficiency for cleaning under low standoffs. The research supplements the findings using a predictive equation to calculate the rate at which flux is removed at various conditions.

Purpose statement

The initial study hypothesized an empirical process cleaning rate equation (Rp=Rs+Rd) where Rp represents the process cleaning rate, Rs represents the static cleaning rate, and Rd represents the dynamic cleaning rate. All cleaning systems are governed by two fundamental principles: 1.) The chemical driving forces that solubilize the residue at a known rate and 2.) The energy applied to the surface of the part to do the work. Nozzles are used in 'spray in air' systems to create jets that carry energy to the surface of the part to be cleaned, rinsed, or dried. The design and layout of the nozzles becomes important if the cleaning system is to be truly optimized. The purpose of this designed experiment is to develop a test method that allows a visual based assessment of the effect on the cleaning rate as a function of energy applied to the board surface by varying pressure/mass flow rate at the board surface, and concentration and temperature of the cleaning fluid at 3, 4 and 5 mil planar gaps. A mathematical model will be developed to help explain our results. It is also our purpose to develop new tools to optimize cleaning of the new Pb-free fluxes.

Research methodology

Quantitative methods discover themes and explore patterns, describe the problem, and predict an outcome. In this experiment, the research helps engineers understand the science of cleaning parts through the study of fluid dynamics, nozzle design, and energy applied to the surface being cleaned. The old premise that increasing the manifold pressure with a bigger pump is being challenged. Fluid mechanics suggests that the energy delivered to the surface is equal to the mass times the velocity squared. Designers of cleaning equipment have historically correlated cleaning efficiency with manifold pressure. Impingement pressure at the cleaning surface is very dependent on the nozzle type and distance from the nozzle manifolds to the surface to be cleaned. Prior measurements of different nozzle types have shown typical pressure drops of 50% for fan nozzles, 75% for conical nozzles, and 25% for coherent nozzles for each inch traveled. This experiment video records, as shown in *Figure 3*, the cleaning process in action. The following variables influencing spray cleaning rate optimization will be used in study.

- Process Cleaning Rate (Dependent Variable)
- Nozzle Design (Independent Variable)
    - Coherent
- Material Variables (Fixed)
    - Flux type
- Eutectic Sn/Pb (Indium SMQ 92J)
- Pb-Free (Multicore LF-300)
    - Cleaning chemistry (Kyzen Aquanox A4630)
    - Chemistry concentration (10% & 15%)
- Process Variables (Fixed)
    - Reflow profile (eutectic peak of 218ºC and Pb-free of 240ºC)
    - Time between reflow & clean (0-4 hours)
    - Wash temperature (120ºF and 140º)
    - Spray impingement pressure at surface (0-10 psig)
    - Location of spray (within one impact diameter)
- Design Variables (Fixed)
    - Component dimensions (glass die was .875" x .875")
    - Stand-off height (3 mil, 4 mil, and 5 mil)
    - Surface materials (glass substrates with glass die)

Test protocol

The test coupon was designed using a top and bottom glass to allow full visibility of the cleaning mechanisms and their rates of cleaning. The top plate was 0.875" X 0.875" square and 0.96mm thick. It is commercially available as a thicker than normal microscope slide cover. The bottom plate was 3" X 3" square and was 0.125" thick with ground edges. It was obtained at a local glass shop.

Four dots of chip bonding adhesive were dispensed on the corners of the smaller plate. The desired stand-off was achieved by placing the appropriate shim stock between the plates. The adhesive was then cured and the shim removed. *Figure 1* illustrates the diagram of the construction process

The test coupon was then heated on a hot plate to 70+10C where gel flux was added at the air gap interface until the gap is filled. The coupons were then transferred to a convection oven and brought to recommended peak temperatures for reflow profile. The coupons were then cooled to room temperature. The coupons are then aged for the appropriate time before running the cleaning test. A 0.078" coherent jet was chosen as it is the standard jet used on the AAT HydroJet/MicroJet inline cleaners.

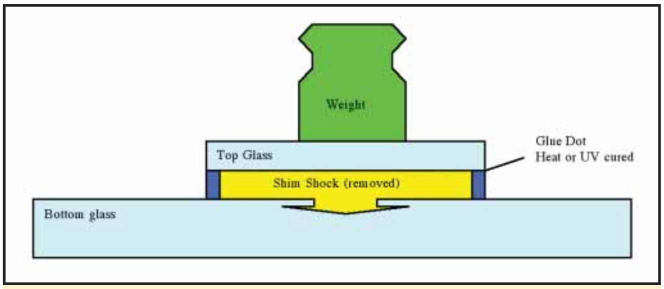


Figure 1. Diagram of the Construction Process.

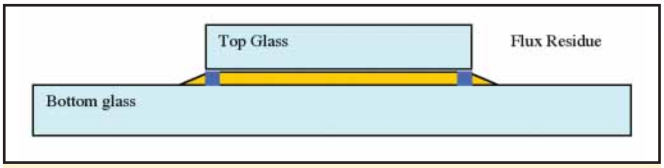


Figure 2. Completed Test Coupon Cross Section.

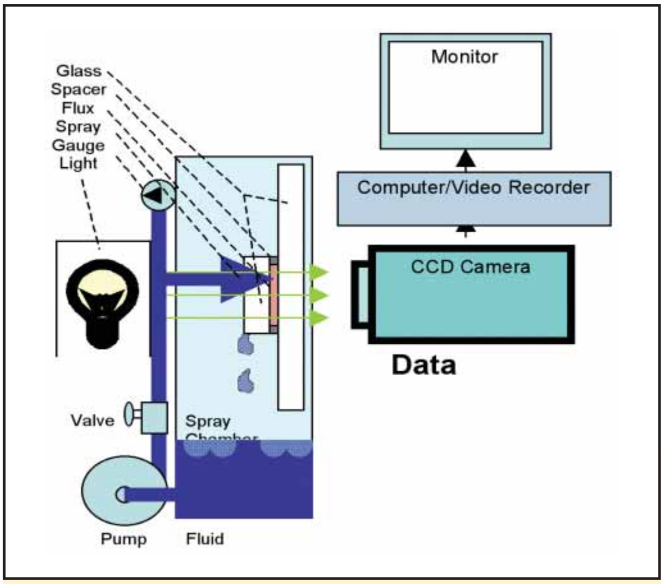


Figure 3. Completed Test Coupon Cross Section.

Test instrument design

Figure 3 shows a system diagram of the test apparatus design we referred by the acronym 'CARL' Cleaning Analysis Recording Laboratory. This system allows the filming and recording of real time cleaning on transparent assemblies/coupons. The capture rate of the video is 30 frames/second (33 milliseconds between captures).

A removable impact pressure sensor was inserted in the fluid jet to measure the impact pressure. *Figure 4* shows a test slide mounted in the viewing window. A solvent rich zone in the center of the slide is visually detectable. The arrows indicate several out-gassing channel exit points in the flux mass. These out-gassing tracks remaining from the solder reflow heat cycle leave weak areas which allow cleaning fluid channels to initiate.

Data analysis

Analysis of the video data collected indicates that the physical process of cleaning the test coupons is a multi-step process governed by several critical parameters. Analysis of the test videos reveal an initial delay in penetrating under the flux filled test slide. Experiments showed that the time required

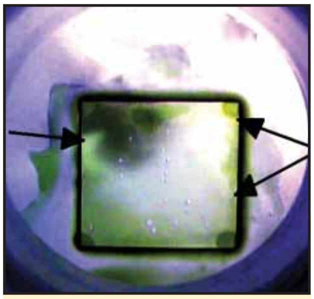


Figure 4. Completed test slide loaded into viewing position.

to break through and begin cleaning the flux under the slide (breakthrough time TBr) is dependent on the wait time between reflow and cleaning for the two flux types included in our matrix. Characterization of TBr for the fluxes tested in this study is discussed later in the paper.

Cleaning time delay

The implications of this measurable delay in initiating the cleaning process can have profound effect on cleaning efficiency. In our initial paper we proposed that the total rate of cleaning (R_p), was equal to the static rate (R_s), plus the dynamic rate (R_d).

It therefore follows that the total time to clean a solder joint is equal to the maximum thickness of the flux residue (DFmax), divided by the average process cleaning rate.

The introduction of an initial delay before any appreciable cleaning occurs changes *Equation 2 to Equation 3*.

Introduction of the T_{Br} factor helps explain the long standing observation that some fluxes get a lot harder to clean with the passage of time. T_{Br} can be measured for any given flux type, cleaning chemistry, impingement pressure, cleaning temperature, and cleaning time delay using the apparatus described in this paper. Our experimentation suggests that all of these parameters have an effect on the time to begin active cleaning. This new metric would now allow today's process engineers to predict and avoid cleaning problems in production and rework cycles.

Cleaning time delay

The hypothesis by the authors of this paper infers that this delay period where the high molecular weight resin molecules are being surrounded by smaller solvent molecules, which penetrate the matrix at different rates, are dependent on the nature of the non-volatile flux residue. If the flux mass is old or has been over-heated, it will contain few of its original solvent molecules added by the flux formulator.

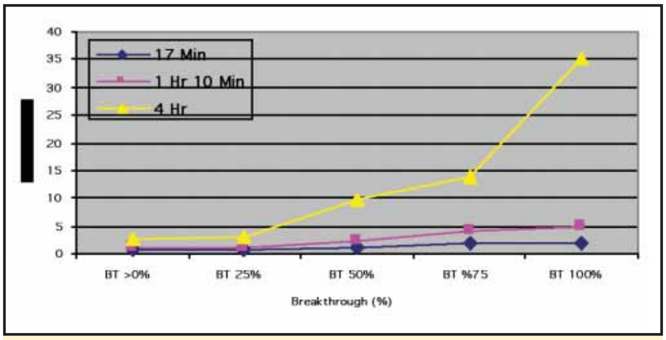
One big difference discovered in the testing was that the Pb-free flux reflow at

Equation 1:
Process cleaning rate equation: $R_p = R_s + R_d$

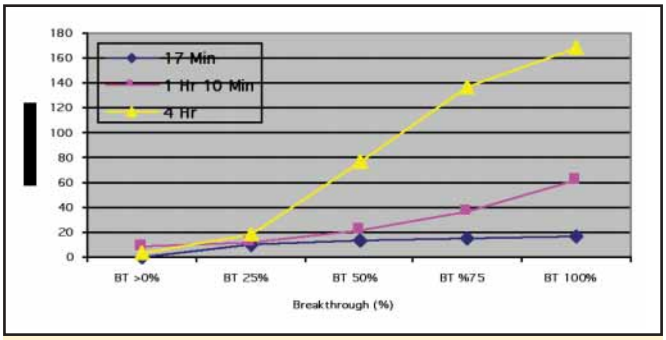
Where:
Average process cleaning rate = R_p
Static cleaning rate = R_s
Dynamic cleaning rate = R_d

Equation 2:
Time to clean = $DF_{max}/R_p = DF_{max}/(R_s + R_d)$

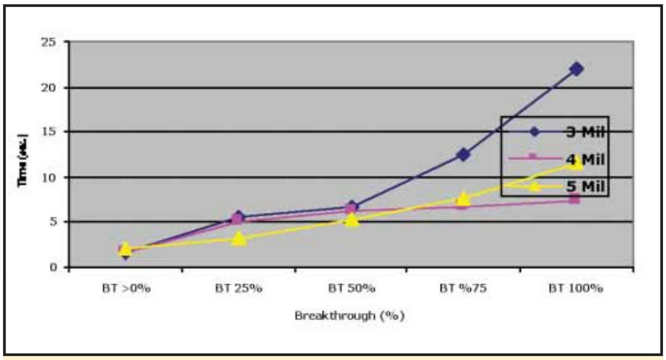
Equation 3: Time to clean
$= T_{Br} + (DF_{max} / (R_p)$
$= T_{Br} + (DF_{max} / (R_s + R_d))$



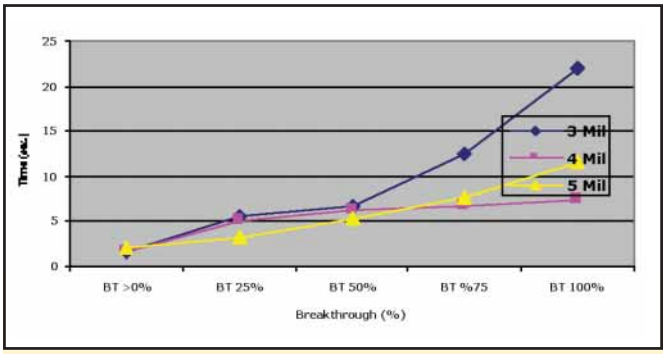
Graph 1. Cleaning rates for several reflow to cleaning wait times for no-clean eutectic tin-lead flux (210°C peak).



Graph 2. Cleaning rates for several reflow to cleaning wait times for Pb-free flux (240°C peak).



Graph 3. Breakthrough time for the T-20 eutectic tin-lead flux residue.



Graph 4. Breakthrough time for the LF-300 eutectic Pb-free flux residue.

240°C peak became much more difficult to clean very rapidly with passage of time following reflow. The no-clean eutectic tin-lead formula, which reflows at 210°C peak, was less subject to the passage of time as correlated to cleaning break-through times indicated on *Graph 1*. Breakthrough rates for the Pb-free flux residue were greater than 10 times longer once the flux cured for 4 hours prior to cleaning as indicated on *Graph 2*.

Graphs 1 and 2 show the deterioration of the cleaning times as a function of the delay following solder reflow heat cycle. Both the 63/37 eutectic and the Pb-free showed significantly longer cleaning cycles as the flux aged. Both fluxes tested show a 10X increase in the time required to fully penetrate the test slide at 4 hours versus cleaning directly following reflow. The higher temperature reflow Pb-free flux averaged nearly 300 seconds to penetrate an 875 mil distance from entry to exit after a 4-hour wait. The large delta change from 1 hour to 4 hours suggests that this trend would continue beyond 4 hours. The rapid deterioration in cleanability suggests Pb-free cleaning will be very sensitive to this parameter. This sensitivity will be much greater than existing 63/37 fluxes. The good news is that this data also suggest that exposed flux with thicknesses less than 5 mils should clean-up even after a 4-hour wait. Trapped flux residue could be a problem.

Standoff height

As the gap from the board surface to the bottom of the die decrease, experience tells us that cleaning becomes more difficult. Graph 3 illustrates the breakthrough time on freshly reflowed T-20 eutectic tin-lead reflowed substrates under 3, 4, & 5 mil standoffs. Breakthrough was 22 seconds for the 3 mil gap, 7 seconds for the 4 mil gap and 12 seconds for the 5 mil gap. The longer time to achieve breakthrough from the 3 mil gap is consistent with expectation. Breakthrough from the 5 mil gap took longer than for the 4 mil gap, which does not correlate with expectations. The flux buildup on the outside of the die may have contributed to this anomaly.

Graph 4 illustrates the breakthrough time for the LF-300 on freshly reflowed LF-300 Pb-free reflowed substrates under 3, 4, & 5 mil standoffs. Breakthrough was 23 seconds for the 3 mil gap, 11.5 seconds for the 4 mil gap and 16 seconds for the 5 mil gap. The longer time to achieve breakthrough from the 3 mil gap is consistent with expectation. Breakthrough from the 5 mil gap took longer than for the 4 mil gap, which once again does not correlate with expectations.

Observed cleaning mechanics

Once the cleaning fluid has broken through the outer 'skin', experiments reveal one of two possible mechanisms will predominate. The first and slower mechanism is based on the observed removal of flux residue in ever increasing diameters of material being cleaned primarily by dissolution to the flux in the cleaning solvent. *Figure 5* illustrates the mechanism of 'concentric' cleaning.

Concentric cleaning tended to be the observed mechanism on older samples ran at lower impingement pressures. Very little concentric cleaning was observed on samples cleaned less than one hour from reflow. Practically all samples tested eventually changed from concentric to channeling as the flux removal mechanism as illustrated in *Figure 5*. The rates measure for concentric dissolution cleaning averaged 10-50 mils/sec in heated 10% chemistry concentration at 10 psig impingement pressure for both fluxes tested in this study. Cleaning rates for channeling driven cleaning tend to be a least and order of magnitude higher than that of concentric driven flux removal.

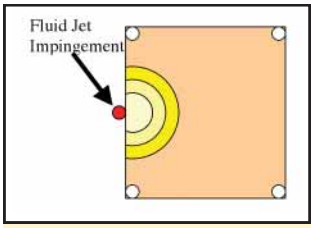


Figure 5. Concentric Cleaning.

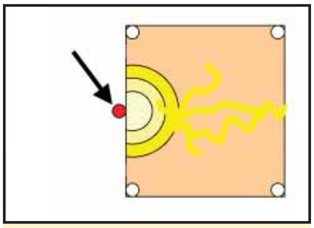


Figure 6. Concentric to Channeling.

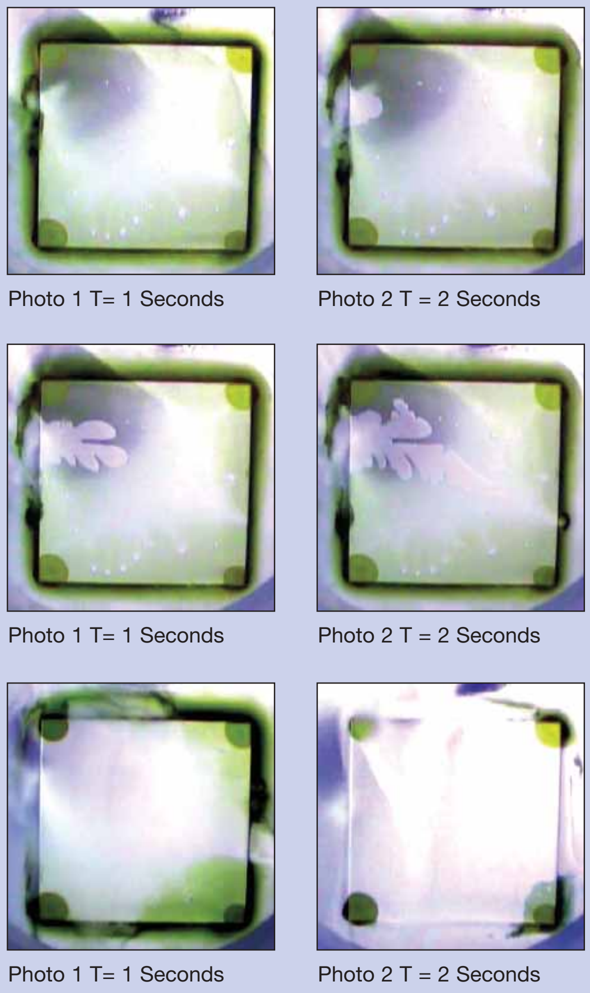


Photo 1 T= 1 Seconds

Photo 2 T = 2 Seconds

Photo 1 T= 1 Seconds

Photo 2 T = 2 Seconds

Photo 1 T= 1 Seconds

Photo 2 T = 2 Seconds

Figure 7. Sequence of the Channeling Cleaning Process.

These channels can form at relatively low impingement pressures if the flux matrix is soft, as can be the case with freshly reflowed flux residue. Test results indicate that both fluxes tested in this research paper required increased cleaning pressure to rapidly form these channels as the flux samples were aged a few hours.

In the one second photo the cleaning jet is beginning to remove the external flux in a concentric pattern of ever increasing diameters. In this photo the cleaning solvent has

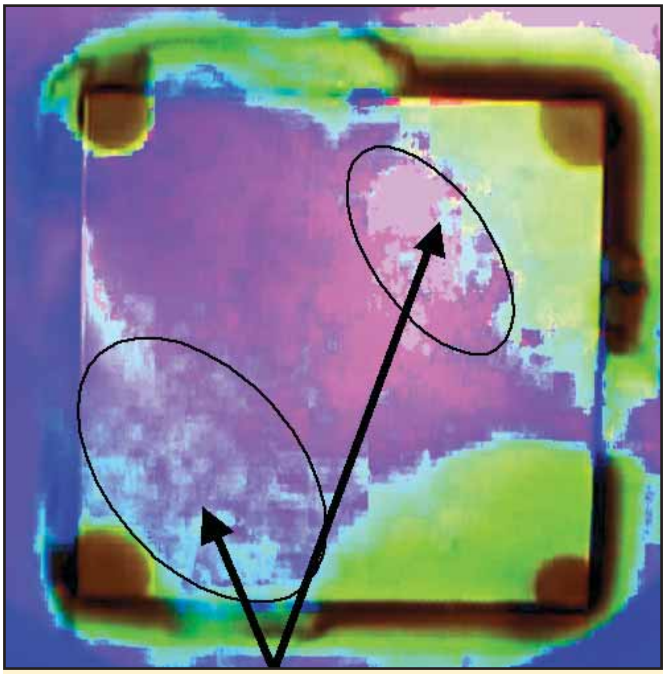


Figure 8. Color Enhanced Version of Photo from Figure 7.

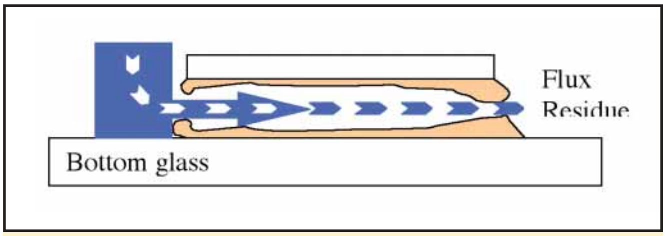


Figure 9. Cross-Section diagram of interim flux removal.

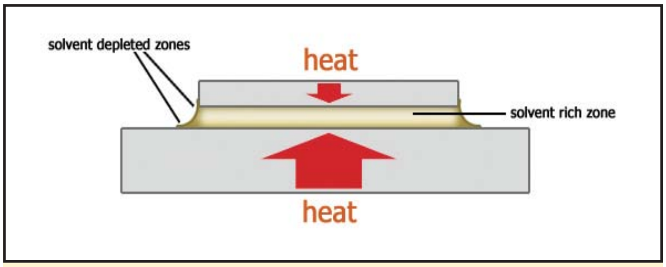


Figure 10. Creation of solvent rich/solvent depleted zones follow solder reflow heat cycle.

just began to penetrate under the slide. In the two second photo the concentric cleaning zone has expanded and there is evidence of rapid channeling beginning as the cleaning fluid reaches the softer interior region of the flux matrix. The three second photo shows the rapid expansion of the fluid channel as it follows the path of least resistance into the reflowed flux matrix.

In the four second photo the cleaning fluid continues to expand and follow what appears to be a weak area created possibly by the flux solvent out gassing in the reflow heat cycle. This weaker path is apparent visually in first 3 photos. Photo 5 shows a fully developed flow pattern where the initial channels have interconnected and cleaning is occurring by dissolving the flux in the flow stream from the interior of the flux matrix to the glass surfaces bounding the flux. *Figure* 8 is a color-enhanced version of Photo 5 showing where the flux center is gone but flux remains on glass surfaces - actively being dissolved.

Figure 9 is a cross section diagram of interim flux removal - note: center clears first, followed by glass surfaces. Flux residue remains around the perimeter of the die adjacent from the nozzle. Once breakthrough occurs, the cleaning solution dissolves the flux residue through the impinging forces pushing the fluids under and out of the cavity.

The middle of the flux is softer and more easily breached by pressurized cleaning solvent because in the soldering process the heat drives the solvent molecules towards the center of the flux creating a solvent rich zone (*Figure* 10). This solvent rich zone is typically softer and more easily penetrated and dissolved. Conversely, a solvent depleted zone is created next to the heated and exposed surfaces. When a zone is solvent depleted it becomes harder and more crystalline and there by significantly more difficult for cleaning agents to soften or dissolve. Referring back to *Figure* 7, Photo 6 shows the flux nearing 100% removal. As expected, the last flux to be removed was the most distant from the impingement area. The rates measured for rapid channel dissolution cleaning averaged 150-250 mm/sec in heated 10% A4630 chemistry concentration at 10 psig impingement pressure.

Data analysis continues in part two of this article, which will appear in *Global SMT & Packaging issue 6.1 (January 2006)*. Part two will also include the authors' conclusions and recommendations as well as information on follow-on research.

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