Root Cause Analysis of Solder Flux Residue Incidence in the Manufacture of Electronic Power Modules

by

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B.E., Mechanical Engineering
Visvesvaraya Technological University, India, 2010

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING IN MANUFACTURING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2011

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ABSTRACT

This work investigates the root causes of the incidence of solder flux residue underneath electronic components in the manufacture of power modules. The existing deionized water-based centrifugal cleaning process was analyzed and hypotheses for root causes of the problem were proposed. The experimentation included cleaning tests using agitation and soak cycles. Parameters such as chemical agent, time and temperature were also tested for these tests. A novel method of residue incidence determination using visual inspection was proposed. Results suggest that the centrifugal process with water is incapable of providing enough agitation to effectively clean the residue. It was also found that product design and architectural causes greatly contribute to cleaning process effectiveness. It was concluded that effective printed circuit board cleaning requires high agitation and efficient product design.

Thesis Advisor: Jung-Hoon Chun
Professor of Mechanical Engineering
Director, Laboratory of Manufacturing and Productivity

Acknowledgements

This work is the result of the encouragement of many people who helped in shaping it and providing feedback, direction and valuable support. It is with hearty gratitude that I acknowledge their contributions to this work.

First, I would like to thank Dr. Jung-Hoon Chun, Professor of Mechanical Engineering and Director of the Laboratory of Manufacturing and Productivity, Massachusetts Institute of Technology for the role he played in his capacity of my thesis advisor. I sincerely acknowledge his invaluable guidance and help during the course of this work.

I thank everyone at Vicor Corporation who has been instrumental in the execution of the work. In particular, I would like to thank my supervisors, Trey Burns, Rudy Mutter, Mohammed Wasef and Eva McDermott for their guidance and suggestions in the area of improvement and implementation of the project.

I am also grateful to Dr. David Hardt, Professor of Mechanical Engineering, Massachusetts Institute of Technology and Dr. Brian Anthony, Research Scientist in the Laboratory for Manufacturing and Productivity at the Massachusetts Institute of Technology for their support and encouragement. I extend a special thanks to Jennifer Craig, Lecturer, Writing and Humanistic Studies, Massachusetts Institute of Technology for her help in editing of this thesis and for her motivation.

I would like to gratefully acknowledge the contributions of my wonderful teammates, Ishan Mukherjee and Nikith Rajendran, whose ideas constantly helped in this work. I personally thank them for being such great friends and colleagues.

Last, but not the least, I would like to thank my family which consistently encouraged me during the course of this work and supported me during my studies at this wonderful institution.

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Chapter 1 — Introduction

1. Introduction

The electronics industry requires sophisticated and dependable electronic power modules for precise applications in the fields of computing, data processing communications and controls. This thesis aims to present a study of manufacturing process improvement in an electronic power module manufacturing plant. The problem dealt with in this work is the incidence of solder flux residue on the printed circuit boards and underneath components even after centrifugal cleaning using DI water. The work includes experimental testing of the root cause hypotheses, the analysis of the experiment results and finally, recommendations to improve the current process.

This requires easy and cost-efficient product manufacturability and reliability. In this work, the focus is on product reliability, with a goal to reduce quality defects related to solder flux residue presence in the circuit.

1.1 Company Background

Vicor Corporation headquartered in Andover, MA is a market-leading provider of electronic power system solutions for the highly specialized electronics industry. The company designs and manufactures modular power components which have applications in various fields such as computing, communications, industrial control, industrial testing and medical and defense electronics.

The company manufactures three types of products— Bricks, VI Chips and Picor components. Bricks and VI Chips are specialized dc-dc and ac-dc power convertors and filters and include power regulators, current multipliers and bus convertors, whereas the Picor range includes high density power conversion circuit components. In this work, however, the focus is on the manufacture and quality improvement of VI Chips.

1.1.1 Product Information and Description

VI Chip refers to the latest series of dc-dc converters released by Vicor which have higher power density, higher efficiency, improved transient responsiveness, lower noise levels and lower costs than the previous series of dc-dc converters. Dc-dc converters are an integral part of many electronic and electrical applications and are used whenever there is a need to either step-up (also referred to as 'boost') or step-down (also referred to as 'buck') the input voltages in order to deliver an output voltage. A typical example could be observed in a car where different electrical appliances like headlights, radio, etc. require different input voltages and, hence, would need a dc-dc converter to convert the input voltage from the car battery to meet the different voltage requirements. This dc-dc conversion can be achieved through the VI – chipset which includes different modules like pre-regulator module (PRM), voltage transformer module (VTM), bus converter module (BCM) etc. Each of these modules has different product architectures, but they can be still produced on the same production line at Vicor.

The PRM, shown in Fig 1.1, can be predominantly associated with voltage regulation, i.e., it delivers a highly regulated voltage from an unregulated input source. Though PRM can be used just as a power regulator, it is usually used in conjunction with the VTM which uses the regulated voltage from the PRM and transforms it according to the demand. Thus a PRM – VTM combination essentially serves as a regulated dc-dc converter. BCM module is a supplementary module which is a fixed dc-dc voltage transformer that can be used along with the regular PRM – VTM combination and usually used to provide intermediate voltages. This modular approach of having three or more different modules (PRM, VTM and BCM) for achieving the function of a dc-dc converter is result of the 'factorized product architecture (FPA)' philosophy introduced and followed by Vicor instead of the regular 'centralized product architecture (CPA)' adopted by the rest of the industry.

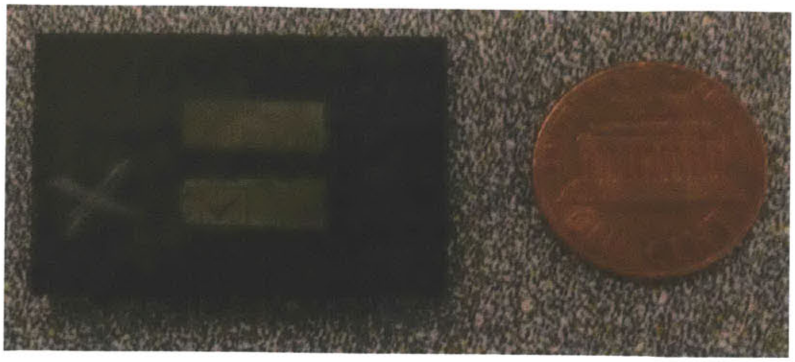


Fig. 1.1: PRM-type VI Chip shown with U.S. 1 cent for scale

1.2 Overview of Thesis

This thesis is the result of a project carried out at the manufacturing facility of Vicor Corporation in Andover, MA from January through August 2011. The work was carried out by a team comprising of Ishan Mukherjee, Nikith Rajendran and the author. The validation of the root cause hypotheses of the problem was done by the author, process development and process optimization studies were conducted by Mukherjee [2] and manufacturing systems analysis was carried out by Rajendran [3]. The thesis has been structured into four parts, each of which describes one of the four stages of the project. Chapter 2 describes the background concepts relating to the processes involved in the manufacture of the power modules and details about cleaning of printed circuit boards after soldering. The problem analysis is presented in Chapter 3, which describes the problem in detail. Chapter 4 contains the review of technical literature and previous work on the problem. The root cause hypotheses and experimental design and procedure are presented in Chapter 5. Chapter 6 discusses the results of the experiments laid out in Chapters 5, while Chapter 7 includes recommendations to the company for process improvement and the conclusions.

Chapter 2 — Overview of Manufacturing Process

2. Introduction

This chapter presents an overview of the manufacturing process in the production of VI Chips at Vicor's facility in Andover, MA. The process flow includes the surface mount assembly for attaching and soldering of components. This chapter also discusses in detail the post-surface mount assembly printed circuit board (PCB) cleaning, its necessity and the methods available for cleaning of boards.

2.1 VI Chip Manufacturing Process Flow

VI Chips are essentially power modules with surface mount devices (SMD) such as field effect transistors (FET), both in multi-wire leadframe package (MLP) as well as ball grid array (BGA) forms, chip capacitors, resistors and chip-scale packages (CSP). Other parts on the chips include transformer core and J-leads. The primary step in the manufacture of VI Chips is the surface mount technology process (SMTP) on the printed circuit boards. Post SMTP, the boards undergo a cleaning process to remove solder flux residues. The subsequent steps are transformer core attach, electrical testing, underfilling, molding, marking and PCB dicing, J-lead attach and final testing. The flowchart in Fig. 2.1 shows the different steps, with the main steps being briefly described in the following sections.

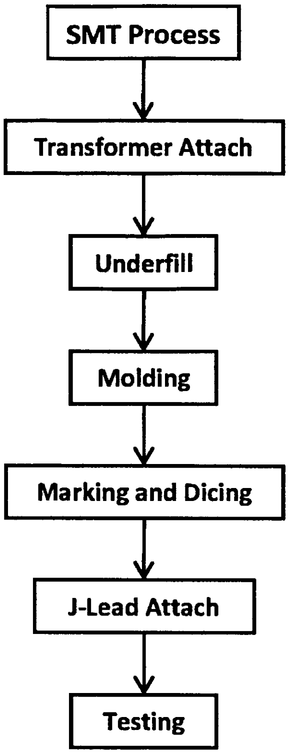


Fig. 2.1: Flowchart of VI Chip manufacturing process

2.1.1 Surface Mount Technology Process

Surface mount technology process is a modern method used to construct electronic circuits in which components are directly positioned and mounted on the PCB. It involves a series of steps in which solder paste is directly applied onto the PCB and then components are mounted and the boards reflowed in a reflow oven to effect the soldering. The flowchart in Fig. 2.2 shows the surface mount process followed at Vicor [16].

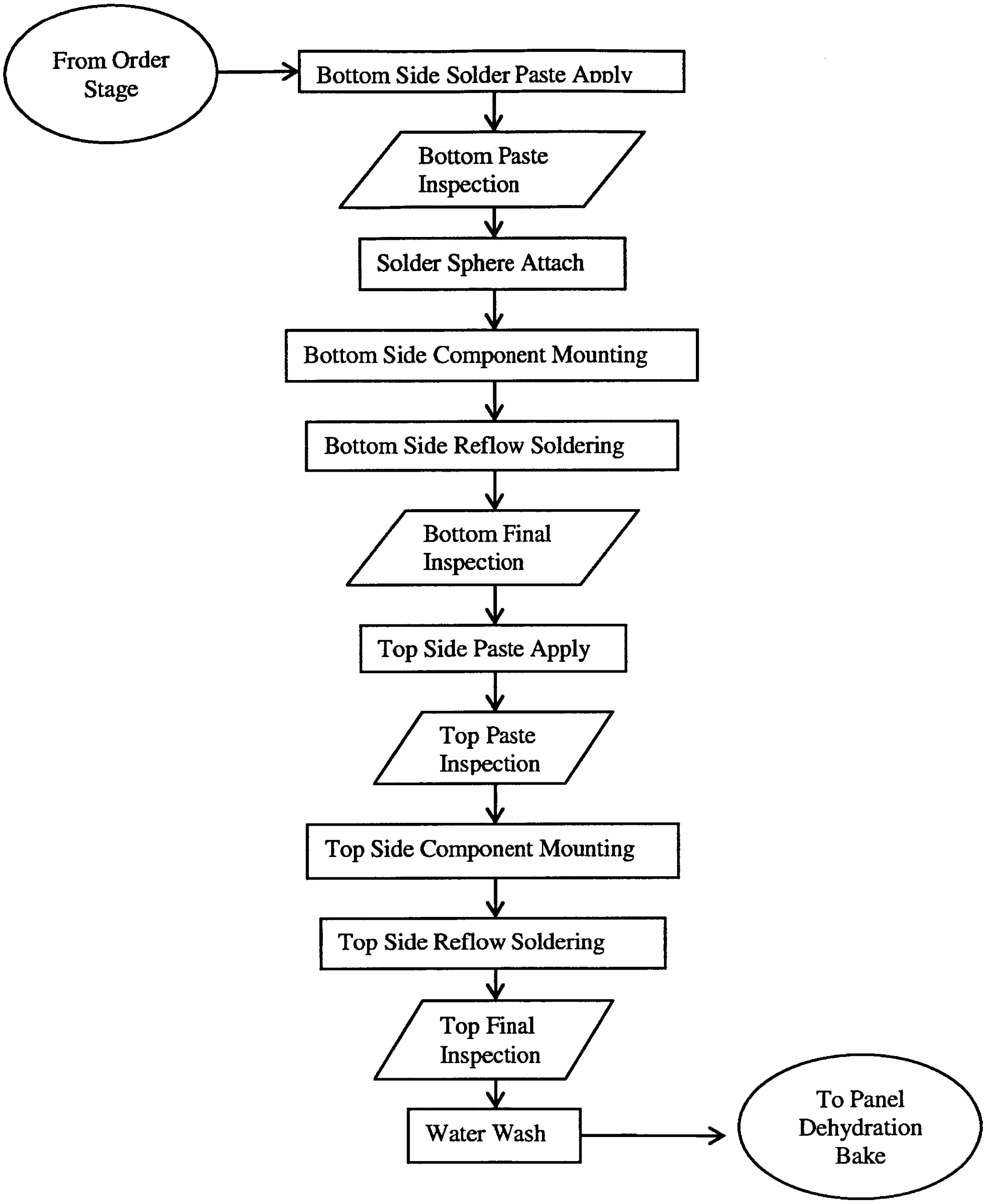


Fig. 2.2: Surface mount technology process flow

2.1.1.1 Screen Printing

The first step in SMTP is screen printing, which involves the use of a stencil with apertures to allow application of solder paste on the PCB only at required positions, with a squeegee applying the paste over the stencil, thus effecting transfer onto the PCB. The solder paste contains the solder alloy and flux. The current paste being used at Vicor is Indium 3.2 HF which contains 88.5% solder alloy and 11.5% flux by weight. The metallic part is a lead-free alloy of 96.5% tin, 3% silver and 0.5% copper, commonly known as SAC 305. The flux is an ORH0 type flux as per the J-STD-004 (IPC-TM-650) standards, which indicates an organic, halide-free flux that forms flux residue which is water-soluble. The flux is used mainly to:

1. prevent oxidation of the solder alloy during reflow,
2. act as a cleaning agent at the solder-component interface, and,
3. provide the necessary tack for the components to stay at their locations till soldering occurs.

2.1.1.2 Solder Ball Attach

This process involves placing spheres of solder alloy, known as solder balls, at certain locations on the PCB. The solder balls are small, having a diameter of approximately 0.5 mm. The solder balls are used only on the bottom side of the PCB where a ball grid array (BGA) forms the J-lead attachment points.

2.1.1.3 Component Mounting

In this step, surface mount devices from a reel are mounted on the solder paste locations on the board. These components are placed precisely at their locations by the machine heads which remove the components from the reel and place them over their designated positions using fiduciary markers on the board sensed by the mounting machine.

2.1.1.4 Reflow

After component mounting, the next step is the soldering process. This is done by making the PCB go through a reflow oven. The reflow line has different temperature zones where maximum temperatures exceed 260°F (≈127°C). The high temperature partially melts the solder alloy contained in the solder paste, making it come in direct contact with the component leads. As the temperature reduces, the solder alloy begins to solidify, thus effecting the soldering. The recent growth in use of lead-free solder pastes due to environmental regulations have led to higher reflow temperatures, which cause flux cleaning problems. It may also be noted that in the manufacture of VI Chips, the bottom side of the PCB goes through reflow twice – once for the bottom side and once for the top side. Post-reflow, the PCB is cleaned with deionized (DI) water to remove any flux residues.

2.1.2 Transformer Core Attach

After SMTP, the next step is attaching the transformer core at the center of each module on the PCB. This core may be made of ferrite or other magnetic materials and plays the crucial role of stepping up or down the voltage. The attach process involves using an epoxy as glue for the core, placing the core on the epoxy, and then curing the epoxy to secure the core.

2.1.3 Underfilling

Due to a difference in the thermal expansion properties of the components and the PCB substrate, there exists a risk of adding thermal strain on the solder joints of the components during any thermal cycle, which may cause joint failure. Underfilling is the process of adding a locking resin between the components and the PCB substrate so that the components are fixed in place. This causes the thermal stress to act on the whole underfilled area, thereby relieving the solder joints of the strain [3]. The resin used is generally an epoxy material.

2.1.4 Molding

Molding is the process of introducing a molding material such as a thermoplastic or resin over the PCB to package the components. During the process, the fluid molding material enters all empty spaces on the PCB, packing all the components in place. Molding can be done by compression molding, injection molding or transfer molding. The molding process is preceded by a dehydration bake and plasma etching for better mold compound adhesion.

2.1.5 PCB Marking and Dicing

After molding, the PCB is marked using a laser and then diced into individual VI Chips using a saw. Subsequently, the individual chips are cleaned by first spraying DI water and isopropyl alcohol (IPA) and then cleaning using a brush. The cleaning is done to remove any contaminants or oxides which may prevent proper J-lead adhesion.

2.1.6 J-lead Attach

In this step, J-leads are attached onto the BGA points on the bottom of the VI Chips. J-leads are specialized leads used to provide an interface between the VI Chip and the external circuit. This is the last step in manufacturing.

2.1.7 Final Testing

After the VI Chips are made, the final step is the testing and quality checks. At this stage electrical tests such as high potential test are performed. Thermal tests are also performed to test for extremely high and extremely low temperature performance.

2.2 Post-SMTP Cleaning

In the Section 2.1.1.4, the process of PCB cleaning after SMTP has been briefly mentioned. This section explains the cleaning process in detail, including why cleaning is done, cleaning methods and existing standards on cleaning.

2.2.1 PCB Cleaning

PCB cleaning is the process of removing solder flux residues from the PCB after the SMT process. The flux present in the solder paste reacts with the metal oxide during the reflow process and prevents further oxidation of the solder metal. The by-product of this reaction is the solder flux residue which gets trapped beneath components and near the undersides of solder balls. During the cleaning process, this residue is flushed out and dissolved by a medium, which may be plain DI water or a chemical solution, using external agitation.

Cleanliness performance is defined using different tests, which consist of mainly two types– visual and chemical-electrical. Visual tests include removing components and visually observing the presence of flux residues, while the chemical-electrical tests measure chemical and/or electrical properties to determine cleanliness. Cleanliness standards and testing have been described in subsequent sections.

2.2.2 Why Cleaning

The solder flux residue, which is trapped between the components and the PCB substrate and near the undersides of solder balls, is electrically conductive as it is made up of ions. As PCBs and modules are subjected to an external electric field, which in many cases involves relatively large potential drops, the diffusing flux residue particles get excited by the momentum transfer of conducting electrons in the circuit. This leads to the particles getting displaced from their positions. A problem may arise when these particles cause bridging between two parts of a circuit, ultimately leading to a short-circuit. This phenomenon is called electromigration. Another form of short-circuiting may be observed when the flux residue forms a bridge over a component. Shorting over components may also lead to component fracture by inducing a differential stress between the component and the surroundings.

Another possible effect of flux residue presence is the improper adhesion of the molding compound and J-leads. For proper adhesion to take place, the surface of the PCB and BGA areas must be free of contaminants such as flux residue. Due to these problems, effective cleaning of solder flux residue becomes imperative.

2.2.3 Factors Involved in Cleaning

A number of factors influence the PCB cleaning performance and can be divided into two major types. One of the main factors is the choice of solder paste. The solder paste may have specific properties which may affect cleaning process. These properties could be physical properties of the flux residue such as viscosity, water solubility etc., chemical properties such as reactivity and corrosiveness and electrical properties such as conductivity. Another major factor is the reflow temperature. With the advent of lead-free soldering, the temperature required for effective soldering has increased, leading to changes in properties of the flux residue. One important factor is the amount of gap present between the component and the PCB substrate, called standoff. Lower standoffs lead to less effective cleaning.

The other set of factors include solvent properties, process temperature, type of external agitation, and wash time. Solvent properties include use of only DI water or DI water with chemicals. Temperature influences cleaning by altering the surface tension of the solvent, altering the solubility and/or by activating the chemical present in the solvent. External agitation forces the solvent into the areas where the flux residue is trapped, thereby improving cleaning performance. Time is also an important factor as it defines the duration for which the cleaning action occurs.

All the above factors when combined effectively can produce good cleaning performance. The choice of factors depends on the requirements for cleaning the PCBs. The challenge is to carefully select and optimize the values in order to achieve the best possible cleaning.

2.2.4 Cleaning Methods

The semiconductor and allied industries have in the recent past been able to come up with many alternate methods of cleaning with each method suited to a particular type of product architecture. These different cleaning methods could be classified based on the nature of their primary approach towards cleaning as either physical agitation or chemical action based methods.

2.2.4.1 Agitation Methods

The three main methods which fall under this category are detailed below:

1. Centrifugal Cleaning

This method takes advantage of the agitation induced by the centrifugal force in a liquid medium which could range from just plain DI water to chemical solutions containing surfactants or solvents. The PCBs are usually held inside this medium and are subject to the centrifugal action during three major cycles namely wash, rinse and dry cycles though the addition of a fourth cycle namely the pre-wash cycle cannot be ruled out. Evidently enough, this method is a batch process with process times averaging around 20 minutes and the temperatures are usually above the room temperature varying between 55°C and 70°C across the different cycles.

2. In –line Cleaning

In-line method of cleaning is a relatively new development which uses water or a chemical solution sprayed at a pressure through custom designed nozzles over the PCBs which continuously move across a line through the machine. Recent advancements made in nozzle technologies by certain companies have resulted in further improvement of cleaning performance. These machines are characterized by higher physical agitation levels, and hence cleaning efficiencies, as well as greater throughput rates when compared to the centrifugal washing machines. However, they require high capital investment and operating costs.

3. Ultrasonic Cleaning

This method uses the physical agitation made possible by the superimposition of the ultrasonic waves originating from a transducer, inside a liquid medium. The superimposed waves produce a cavitation effect where vacuum bubbles are constantly formed and undergo implosion. This results in easier access under the components for the cleaning medium. The use of ultrasonics, however, has also been known to have mildly destructive effects on minute surface mount devices.

2.2.4.2 Chemical Methods

This category includes methods in which the chemical action is predominantly responsible for cleaning. Many commercial companies have introduced different chemical solutions that achieve the purpose. Most of these chemical solutions are either surfactants or solvents that tend to drastically reduce the surface tension of DI water so that it is able to reach the minute pockets and the remotely accessible areas of the product.

2.2.5 Current Cleaning Process

After the final reflow process, the boards which were part of a single-piece flow are placed in a cartridge. Such a cartridge can hold 10 boards at a time. The cartridge is carried over to the visual inspection station, where the boards are inspected for improper component placement or solder joint faults. The next step is the PCB cleaning process, which is the final stage in the SMTP line. The cleaning system in place consists of two centrifugal water washing machines which can each clean two cartridges at a time, i.e., 20 boards. The cleaning medium used is DI water. The cleaning occurs in three steps, viz., wash, rinse and dry, with temperatures of 65°C, 72°C and 110°C, respectively. Fig. 2.1 shows a centrifugal cleaning machine with cartridges. The cleaning process is followed by a dehydration cycle where the boards placed still placed in cartridges are baked to remove any trace of moisture which could affect post-surface mount processes such as underfill and molding.

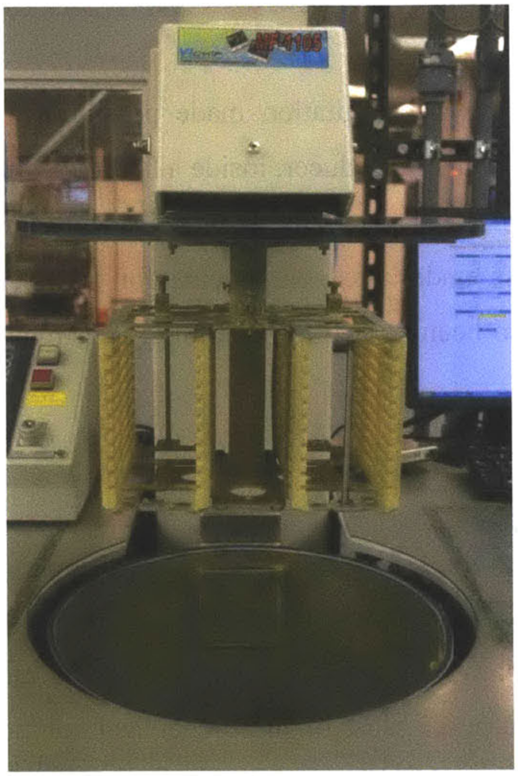


Fig. 2.3: Centrifugal cleaning machine

2.3 Process Control and Testing

As with any other manufacturing process, the cleaning process too has its own set of process control tests which could be used for monitoring the process. These tests vary in the time taken for testing, costs involved and also in the requirement of manual supervision.

2.3.1 Process Control Tests

Though both ionic and non-ionic contaminants are found on the surface of the board, the ionic contaminants are of particular interest since they have the potential to cause electro-migration and similar other problems. Tests include ionic contamination test, ion chromatography (IC), surface insulation resistance (SIR) test, Fourier transform infrared spectroscopy (FTIR) and visual inspection. These have been discussed in this section.

2.3.1.1 Ionic Contamination Test

The ionic contamination test also known as the resistivity of solvent extract (ROSE) test, is predominantly used in most of the industries thanks to its simplicity as well as its versatility. In this test, the boards are immersed in DI water for about 5 minutes and later the DI water is tested for contamination which is measured in terms of μg of NaCl per square inch. But this method also suffers from serious deficiencies as it can measure only ionic contamination and does not reveal the source of the contamination. In many of the cases, the contaminants present in inaccessible areas go undetected in this test.

2.3.1.2 Ion Chromatography

Ion chromatography is a more sophisticated and time consuming test where the boards are kept in clean ion-free bags and then placed in a bath containing 75% alcohol and 25% water and maintained at $80^{o}C$ for at least an hour. This test color codes the different types of ions present on a board and most importantly indicates the source of these ions.

2.3.1.3 Surface Insulation Resistance (SIR) Test

Surface insulation resistance (SIR) test measures the contamination by conducting an electrical test across a solution in which the board has been soaked and then measuring the current which gives an idea of the resistivity of the solution which in turn can be directly correlated to the level of contamination.

2.3.1.4 Fourier Transform Infra-red (FTIR) Spectroscopy

This is another optical inspection test which scans the board with infra-red light and uses the resultant image to analyze for contamination. This image is then compared with industry standards to identify the contaminants. This test is most generally used in the industry to identify the organic contaminants.

2.3.1.5 Visual Inspection

Visual inspection gives the most detailed result among all the different tests but it is a laborious process and requires manual supervision. At a magnification of 50X, it is possible to observe the flux residues on a VI Chip. The visual inspection is preferred especially when there is a need to know the location and the distribution of the flux residues.

2.3.2 Inadequacy of Current Testing Methodology

At present, the ionic contamination test is regularly carried out on the products coming out of the washing process and the results of the test are plotted on control charts which are then used for monitoring the process. On reviewing the test results and the control charts, it was observed that the ionic contamination levels do not cross specification limits, as described by industry standards. This occurs even though there have been flux residues observed on the board surface and underneath components. The main reason for this is that the ionic contamination test, in essence, measures the resistivity of the solution based on the amount of residue washed and dissolved, rather than the amount of residue on the board. Thus, the test results in a number of false negatives for flux residue presence.

Chapter 3 — Problem Statement

3. Introduction

As explained in Chapter 2, the PCB cleaning station or the water wash station comes after the second reflow process and the manual inspection stage. The DI water based centrifugal washing machine is responsible for removing all flux residue and other contaminants from the surface of the boards and from underneath the components present on them. However, over a period of time it was found by Vicor that repeated quality tests showed the presence of flux residue on the products. With Vicor's objective of maximizing product reliability, it was imperative that this problem be investigated and corrected. This chapter discusses the problem in detail, which will be useful in proposing of the root cause hypotheses mentioned in Chapter 5.

3.1 Problem Description

The final testing of all module circuits is carried out after the last stage of production which is the J-lead attaching stage. The tests performed check all circuits for their electrical integrity. When circuits are found faulty, they are sent to the quality assurance (QA) department for quality analysis. These tests involve a wide range of testing procedures, of which destructive testing is the main procedure, where surface mount components are pried off the board and then inspected for integrity of solder joints, solder shorting, presence of flux residue etc.

Over a period of time, nearly all packages were found to have flux residue presence. Flux residue was observed on the boards and also under surface mount components. It must be noted here that as the test cycle is at the end of the production line, the cause of fault cannot be precisely attributed to a particular process and only plausible causes can be proposed. However, it was believed that this flux residue was causing a number of quality defects and that the board cleaning process needed to be improved. Thus, it was required that the root causes responsible for the presence of flux residue be identified and subsequently remedial measures be undertaken.

3.1.1 Areas of Residue Incidence on PCB

The preliminary visual inspection of products revealed the presence of flux residue in nearly all inspected product types. The residues were present on the board around solder joints and under certain components.

a) Around Solder Joints

On preliminary inspection, white colored flux residue was observed on the surface of the PCBs. As shown it the Fig. 3.1 and Fig. 3.2, the residue appeared to be a random scattering of white colored particles on the board surface or closely surrounding solder joints. Further inspection revealed that the particles were water-soluble flux residues left behind due to inefficient cleaning.

Fig. 3.1: Flux residue surrounding solder joints of BGA FET and on the board

Fig. 3.2: Flux residue near FET solder joints

b) Under Low Standoff Components

The term 'standoff' refers to the distance between the bottom surface of surface mount components and the top surface of the board. As the products being manufactured are highly compact, some components such as the 1210 chip capacitors and MLP FETs have standoffs as small as 0.05 mm. Fig. 3.3 illustrates the standoff for a MLP FET which is about 0.051 mm.

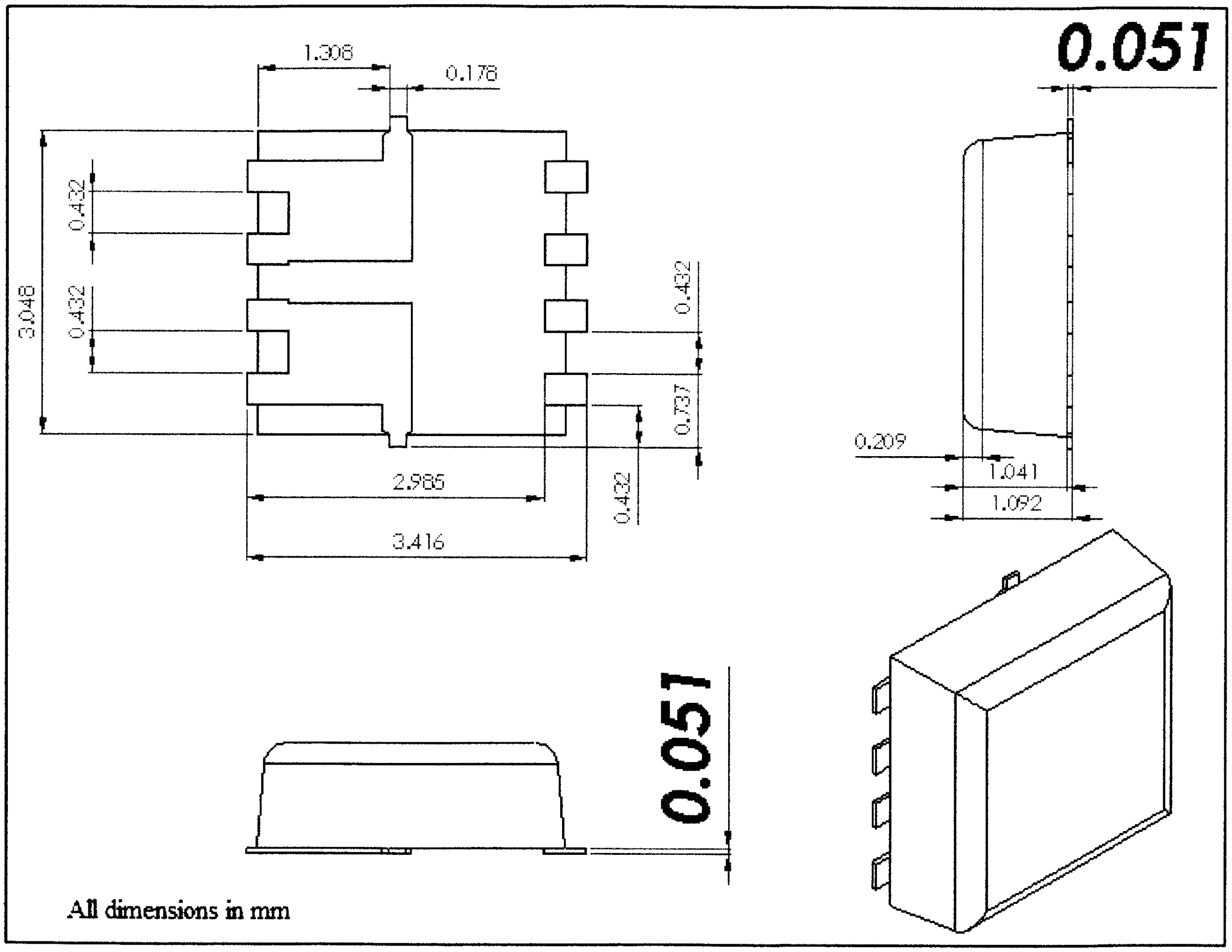


Fig. 3.3: Illustration of MLP FET showing standoff

QA inspection revealed that components with low standoffs were the most critical for cleaning performance. Most residues were found beneath such components. Fig. 3.4 and Fig. 3.5 show the residue under the MLP FET. Fig. 3.6 and Fig. 3.7 show the residue under 1210 chip capacitors and a BGA FET, respectively.

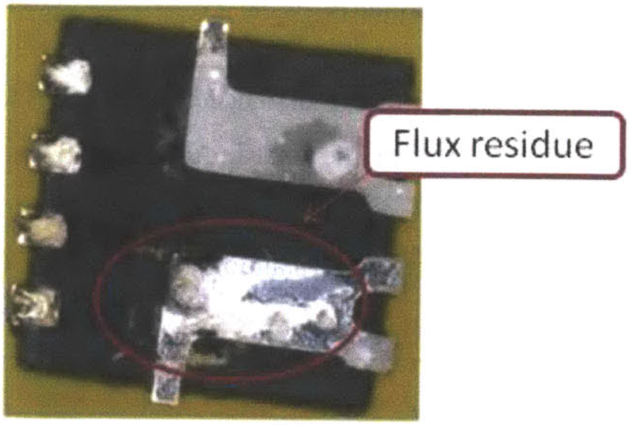


Fig. 3.4: Flux residue on MLP FET underside

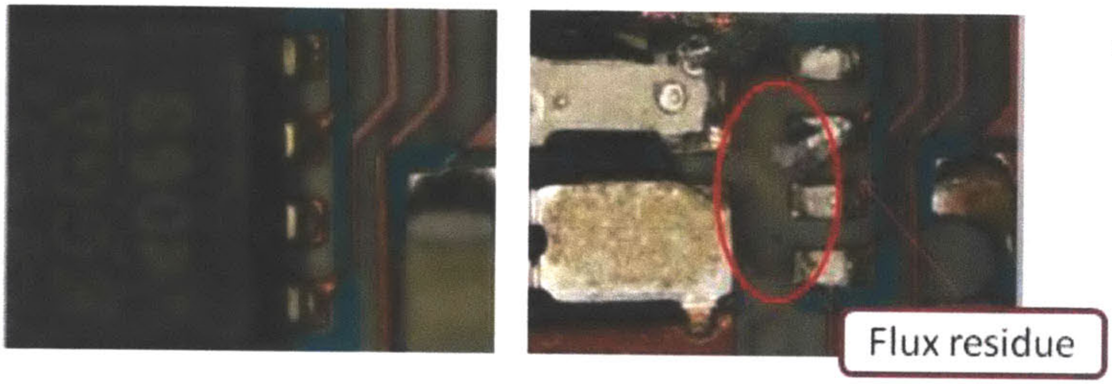


Fig. 3.5: Flux residue under MLP FET

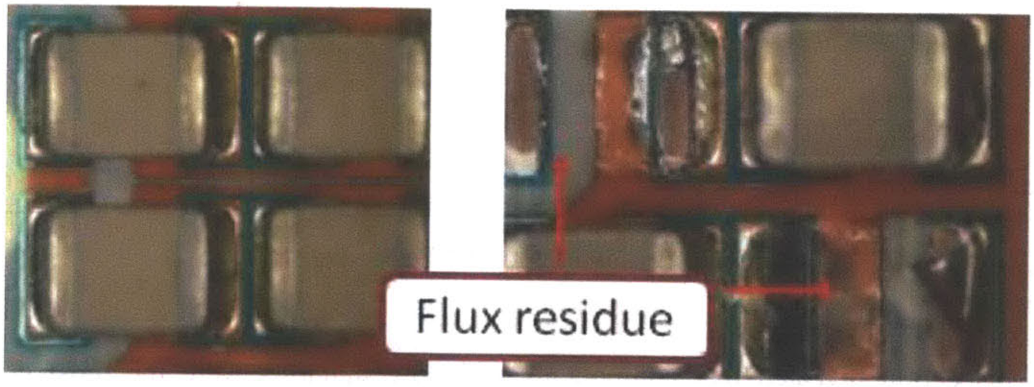


Fig. 3.6: Flux residue under 1210 chip capacitors

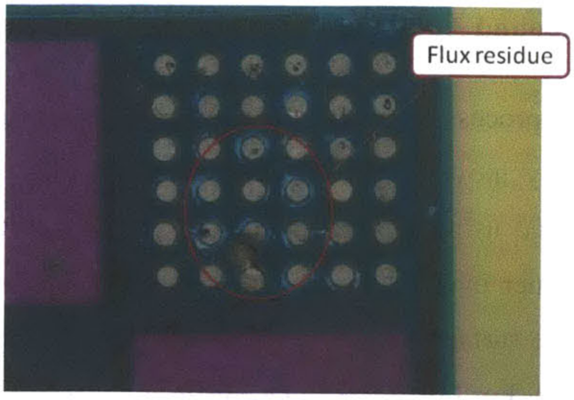


Fig. 3.7: Flux residue under BGA FET

3.1.2 Effects of Flux Residue

The presence of flux residue on the surface of the PCB and under components adversely affects the product reliability. In Section 2.2.2, three major detrimental effects of inefficient cleaning were highlighted, which have been explained below.

3.1.2.1 Electromigration

Electromigration is an electrochemical process wherein metal on an insulating material, in a humid environment and under an applied electric field, leaves its initial location in ionic form and re-deposits at a different location [4]. Such a migration may reduce isolation gaps and ultimately lead to an electrical short circuit. This phenomenon can lead to poor circuit reliability.

The presence of flux residue on the circuits can provide a path for development of a potential. The process starts if a thin continuous film of water along with residue forms an oppositely charged electrode. Positive metal ions are formed at the positively biased electrode anode, and migrate toward the negatively charged cathode. Over time, these ions accumulate as metallic dendrites, reducing the spacing between the electrodes, and eventually creating a metal bridge. The formed metal bridge would cause solder shorting when potential is applied, thus, inhibiting the proper functioning of the circuit.

3.1.2.2 Poor Mold Compound Adhesion

In the manufacturing process once all the components are mounted onto the PCB and the boards are underfilled, they move to the molding stage. In this process, the module circuit components are encapsulated using a molding compound. This process involves introducing a molten thermosetting polymer over the components which is then allowed to cool and form a hard cover to protect all the surface mount components. This process involves adhesion of the mold compound to the PCB. For this to take place efficiently, the PCB should be clean and free of any contaminants. Thus, the presence of flux residue can reduce mold compound adhesion.

Furthermore, Vicor is working to replace the current underfill process by a 'molded underfill' process. This new process would obviate the underfill stage as the mold compound would then be used for both molding the product and also as the underfill material. As the mold compound has lesser surface tension than the conventional underfill material, the presence of flux residue and contaminants would make underfilling much more difficult.

3.1.2.3 Improper J-Lead Attach

Similar to the issue of poor mold compound adhesion, the attachment of J-leads is severely affected by the presence of flux residue near and around the BGAs. The occurrence of flux residue on the BGA can hinder proper soldering of the J-leads to the BGA. The J-lead is attached to the BGA in the same way as all other components; it is first placed onto the BGA and then the unit is passed through a reflow process where the high temperature solders the J-lead to the solder balls. Hence, if flux residue is present on the surface of the solder balls and also around their periphery, the solder joints formed would be contaminated, producing solder joints which would lack the structural strength desired.

3.2 Problem Statement

As illustrated in Section 3.1, flux residue was prevalent near or under nearly all products inspected, and was significantly under the low standoff components. The DI water based cleaning process explained in Section 2.2.5 has four primary process parameters involved. The process of removing flux residue from the PCB and its components depend on the following parameters:

1. Agitation
2. Chemical action
3. Wash time
4. Temperature

Agitation is the parameter that forces water into low standoff areas, loosens up the residue, and forces the flux residue outside. The amount and type of agitation produced with the cleaning medium used is completely dependent on the wash technique used. In the currently used centrifugal cleaning, agitation is produced by the rotation of container producing fluid flow against the board in either direction. Fig. 3.8 shows how the architecture on the bottom side of components determines the path of fluid flow during the cleaning process. If the flow of fluid through these channels is not sufficient, flux residue stays back and the component is not cleaned with desired effectiveness. It was seen that flux residue incidence was low where a fluid flow channel is present.

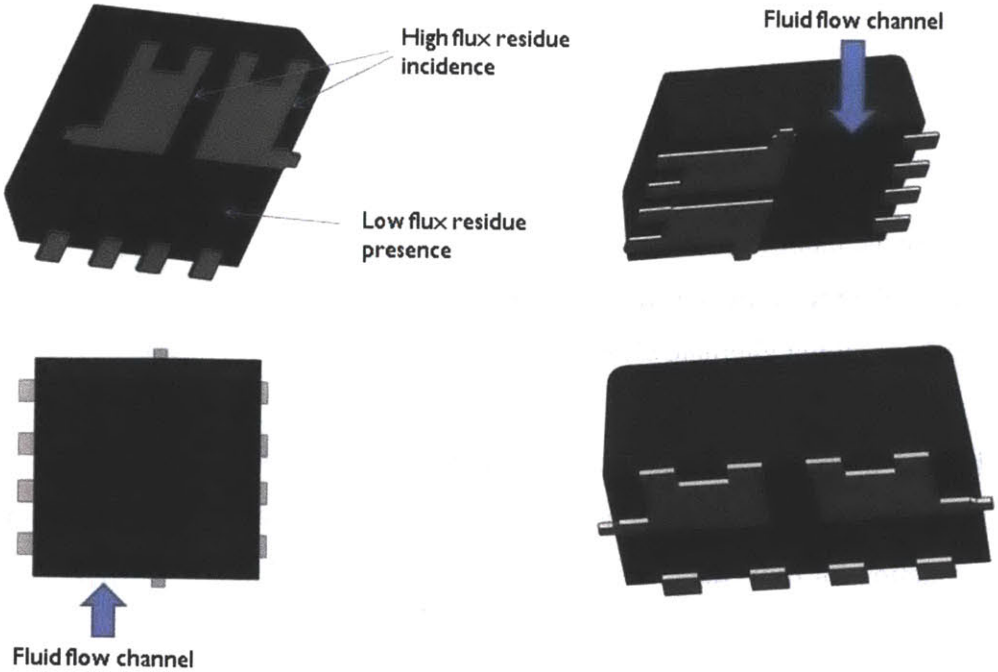


Fig. 3.8: Illustration of fluid flow beneath MLP FET

Although the residue is completely water soluble in nature, its dissolution can be enhanced by using an alkaline chemical agent. DI water is pH neutral and so the surface tension and chemical activity of the solvent is not altered. Thus, use of alkaline solution or surfactants would reduce the surface tension resulting in better flow and would also dissolve the flux residue faster. Time and temperature are the two other critical parameters responsible for effective cleaning. The more time a board is exposed to agitation, the better the cleaning. Also, with an increase in temperature, the surface tension and viscosity of the cleaning medium reduce, resulting in easier flow.

It was observed that most low standoff components had large amounts of flux residue present beneath them. This indicated that the current DI water based centrifugal cleaning method was ineffective in cleaning and dissolving the flux residues. Further, it was seen that a number of factors influence cleaning performance. Thus, it was required to determine the reasons for ineffective cleaning so as to help identify an alternate cleaning process.

3.3 Project Objectives

In the previous sections it was seen that effective removal of solder flux residue is vital for product manufacturability and reliability. Thus, it becomes imperative to determine optimal process parameters and methods for the PCB cleaning process. In this regard, the following were the objectives of this research work:

1. Identify the main factors involved in the cleaning process
2. Identify the root causes of flux residue incidence
3. Develop optimal/alternate cleaning process

In Chapter 4, technical literature and previous work have been reviewed in order to understand the problem. In the subsequent chapters, the analysis of the current cleaning process and experimentation for root cause identification have been included.

Chapter 4 — Literature Review and Previous Work

4. Introduction

In this chapter, a review of literature and previous work done in the field of post-SMTP solder flux residue cleaning has been presented. This forms the basis of understanding the problem and the methodology that was adopted during the execution of experiments for root cause analysis. In the initial section, brief summaries of some of the technical papers published in this subject are given. This is followed by the review of some of the previous work done in this area at Vicor Corporation and chemical vendor companies on behalf of them.

4.1 Review of Technical Literature

The importance of efficiently removing solder flux residue from components is well appreciated within the electronics manufacturing field [5]. With the increasing miniaturization of electronic assemblies, electronic products are moving to smaller size, higher density, higher speed and lower cost [6, 7]. Furthermore, in the mid 1990's environmental regulations resulted in the implementation of international standards such as RoHS and REACH [7] which led the electronics manufacturing industry to adopt halogen-free and lead-free soldering. As a result of such technological advancements and environmental regulations, designers and manufacturers are faced with the challenge to maintain acceptable standards of cleanliness.

The ability to remove flux residue after a soldering process from an electronic component is dependent of various factors of which product architecture and the solder flux used are the most important [8]. The family of products studied in this work is comprised of surface mount devices which are either chips scale packages (CSPs) or ball grid array (BGA) components. BGA components such as FETs have significantly higher standoff heights as compared to CSPs

[9]. The standoff for a BGA component can range from 457 μm to 508 μm while a CSP could have standoff heights less than 50 μm. Research by Mearig and Goers [9] has shown that cleaning under BGA components is not a difficult process using semi-aqueous cleaning solutions. On the other hand, the significantly smaller standoff heights of CSPs have found to be very difficult to clean by numerous academic and industry studies [6, 8, 10-12]. The standoff heights of CSPs were found to vary from component to component due to variation in manufacturing of their lead frames and the minimum standoff height was found to be 30.5 μm [11]. To tackle the problem of cleaning components with low standoff heights, the industry has strived to achieve the optimal combination of the type of solder flux and the cleaning technique for it.

After the implementation of environmental regulations, the two major families of solder flux used are conventional lead-free solder fluxes and no-clean solder fluxes. A majority of the industry leaders have adopted no-clean fluxes [6] due to the non-requirement of a cleaning process which facilitates it to be used in complex product architectures [10]. However, it has been seen that in some cases even no-clean solders are cleaned to remove contaminants [11], which may produce process variations during component placement. The products researched in this study were manufactured using a water-soluble lead free solder paste as prior experiments using no-clean solder fluxes had resulted in high assembly failure rates. The change in the composition in lead free solder pastes has had significant effects on the physical characteristics of the solder paste such as the melting point and the required reflow temperatures [10]. Due to higher reflow temperatures there is a high probability of a tin salt formation along with increased bonding between the fluxes and the panel base. Hence, although lead-free solder systems are environmentally desirable, the cleaning of the flux residues is more difficult [8].

With the adoption of complex solder systems the need for an appropriate cleaning process is critical. In seminal studies such as those done by Hansen *et al* [4] and Ghaffarian *et al* [11], in-line DI water cleaners were used. However, such cleaning systems are associated with significant capital costs and running costs. Lee in his studies [5, 8, 10] has stated that mechanical agitation is an important factor in the cleaning process techniques such as spray-in-air, spray-under immersion, ultrasonic waves and centrifugal cleaning have been found to show consistently good results. The chemical concentration of the solvent used during the cleaning process has also been found to be a critical factor [8]. Semi-aqueous and aqueous solvents when used along with appropriate agitation techniques give good cleaning efficiencies. Lee also states that test procedures such as surface insulation resistivity (SIR), ionic contamination and ion chromatography have characteristics which make it suitable for a particular flux type and with each test having its advantages and disadvantages.

4.2 Review of Previous Work

Prior to the work in this thesis, a study [13] was carried out by Vicor to optimize their DI water based centrifugal cleaning process, which was being used in the surface mount assembly line. The study found that the temperature of cleaning water, extended wash time, position of product in washing fixture and wait time after reflow did not have significant effects on cleaning performance. Work regarding adoption of an alternate cleaning method by also conducted by cleaning chemical and equipment vendors on behalf of Vicor [14, 15]. The alternate cleaning techniques tested were in-line, ultrasonic and centrifugal cleaning with the use of chemical agent. Different chemical concentrations, wash times and temperatures were tested for these processes. It was found that ultrasonic and in-line cleaning gave the best results. The use of higher chemical concentrations and a temperature of 150°C were recommended.

Consequently, the proven ineffectiveness of the DI water based centrifugal cleaning process emphasizes the need for adopting a technique that is best suited to the architecture of the product being manufactured and the water-soluble lead-free solder flux being used. This thesis presents the study that was carried out applying findings from literature mentioned above to develop and optimize an efficient cleaning process.

Chapter 5 —Problem Hypotheses and Design of Experiments

5. Introduction

From previous work mentioned in Chapter 4 and the preliminary observations made, it was found that specific variables such as properties of the solder paste, wash time, agitation and temperature can greatly influence cleaning process performance. Thus, based on this, the hypotheses for causes of the solder flux residue presence have been proposed in this chapter. Further, those variables which can be characterized as process parameters have been identified and based on which, the design of experiments for root cause identification has been detailed.

5.1 Factors Involved

The cleaning process carries out the basic process of removing flux residue from the surface of the board and from under surface mount devices. This process of removal of the water-soluble flux residue can be carried out either physically by washing it out or chemically by making standoff access easier and dissolving the residue. As a result, the principal factors that determine process effectiveness are generating the required agitation and providing an efficient agent which aids dissolution of the residue in the cleaning medium. These factors can be further broken down into the four process variables that determine the performance of the cleaning process and qualify as process parameters, viz., agitation, chemical concentration, wash time and wash temperature.

5.1.1 Agitation

The type and magnitude of agitation determines whether enough force is generated for the solvent to flow into low standoff region. This would- firstly, help loosen the flux residue and flush it out and, secondly, expose the flux residue to the solution which would simply dissolve it. In the current process, agitation is provided by the centrifugal action of the wash tank and also by a set of nozzles during the rinse cycle. As the DI water filled tank rotates and counter rotates, enough turbulence is created inside the tank for the DI water to flow into low standoff regions. The nozzles provide additional agitation by spraying DI water into low standoff regions to wash and rinse the PCBs. Along with agitation, another important factor is the duration of the wash process. Higher wash times would provide more exposure time of the boards to DI water for loosening the flux residue. As the agitation generated by a centrifugal machine is less, longer wash times would allow for a much higher chance for the DI water to access low standoff regions.

5.1.2 Chemical Action

The chemical characteristics of the solution determine how effectively the flux residue is dissolved. Solutions with specific chemical agents act by reducing the adhesion of residue to the PCB by loosening the residue. They also reduce the surface tension of cleaning medium for effective penetration into low standoff areas and then chemically act on the residue and help dissolve it. The current process does not use any form of chemicals and uses only DI water during the wash process. This is because of the belief that with enough agitation, water would be able to access low standoff regions to dissolve flux residue. It is to be noted that as the flux residue is completely water-soluble in nature, and thus, water should be sufficient to dissolve it completely and any other chemical agent may only assist in reducing the surface tension to enable DI water to flow into low standoff regions. Thus, the concentration of the chemical agent would also be an important factor in determining cleaning performance. Higher concentrations would mean lower surface tension of the cleaning medium and more ability to dissolve the residue. As mentioned above, wash time would also be of importance here as more the time the cleaning medium is in contact with the board, the more the chemical agent will be able to dissolve the flux residue. Another factor critical for cleaning with a chemical agent would be the temperature of the cleaning medium. As solubility increases with increase in temperature, higher process temperatures would improve cleaning effectiveness; as explained in Chapter 4, this phenomenon has been proven in past study and experiments. Also, when washing is done using chemical agents, the chemical activity increases with temperature. Other benefits of higher temperature are improved solubility of residue and lower surface tension of water. As the products under consideration are high performance and highly sensitive high temperatures could possible adversely affect product performance, as a result the wash cycle temperatures have been fixed in the range of 55°C to 65°C.

5.2 Problem Hypotheses

The problem statement and the effects of the problem were highlighted in Chapter 3. It was seen that the main problem was that of the low standoff under certain components which prevents effective cleaning of the solder flux residues. Also, after reviewing technical literature as seen from Chapter 4, the physics of the working of the cleaning process was studied. This involved understanding the flux chemistry, agitation effects, chemical methods of cleaning and the dynamics of flow of the cleaning medium. This led to formulation of hypotheses for the flux residue problem. The hypotheses are shown in Fig. 5.1 with the help of a chart.

5.2.1 Flux Residue Adhesion

The first premise about the large amount of flux residue incidence under components is that the adhesive force between the flux residue and the surface under the components is high. If this force is high enough, it could prevent the water or the cleaning medium from dissolving and cleaning the flux residue. In the boards, there are three kinds of surface materials under a component, viz., PCB laminate, solder mask and copper pad. Each of these can influence the amount of adhesive force acting between the layers of the surface and the flux residue. However, it has been observed in preliminary studies that the incidence of residue is irrespective of the type of surface, and occurs in all three cases. This indicated that the adhesive force could be a major factor determining cleanliness.

To support the premise of flux residue adhesion, two important reasons were put forward. Firstly, the solder paste used may have certain properties which do not allow proper cleaning. This may be due to the fact that the residue formed has a high coefficient of friction which causes high sticking or adhesive forces. Secondly, it was observed that the bottom side of the boards had a higher incidence of flux residue. It was observed that a burnt-in, brown residue was observed under the MLP FETs on the bottom side. This may be due to the fact that the bottom side goes through reflow twice- first for the bottom side and second for the top side. It has been highlighted earlier that the use of lead-free solder pastes has led to higher reflow temperatures. Thus, higher temperatures combined with twice reflow may cause burning-in and settling of flux residue which becomes difficult to remove.

5.2.2 Ineffective Cleaning Process

The fluid flow dynamics and cleaning mechanisms are defined by the cleaning method employed. As described in the previous section, the current cleaning method uses the centrifugal agitation to force water into the component standoffs for cleaning. However, if the agitation is not enough, the water cannot enter the standoffs. This led to the hypothesis that the water does not reach the residue with enough agitation or effectiveness in the current process. The cleanliness in the centrifugal method also depends on a number of factors which include orientation and position of boards, resistance offered by cartridges in which the boards are placed and the time for which the boards are subjected to washing. A study conducted at Vicor as reviewed in Chapter 4 suggested that orientation and position effects were not significant. This indicated that the amount of time and force could be important factors in cleaning performance.

Another related reasoning for ineffectiveness of the cleaning process was hypothesized to be due to surface tension effects. The current water wash process uses DI water to clean the boards. However, plain DI water has a high surface tension, which does not allow it to enter the low standoffs and effectively clean the residues underneath components. This is because the high surface tension aggregates the water molecules together outside of the component, preventing entry into the standoffs. This would mean that lower surface tension of the cleaning medium would result in better cleaning.

5.2.3 Component Design and Architectural Causes

During the observation stage, it was primarily seen that flux residue found under certain components was always more than others. This gave rise to a premise that component design and PCB architecture could be a possible cause of the problem. An example would be that of the MLP FET, which although, has a similar standoff as some other components such as the 1210 chip capacitors, tends to have more flux residue underneath it. This may be related to the footprint of the component which has small channels for fluid flow.

Product architecture can also play a significant role in determining cleaning performance. One of the key challenges is allowing a fluid flow channel underneath components. However, presence of solder mask or copper pads below components due to product design limitations can restrict water flow. Also, with decreasing size of electronic products, components need to be spaced more closely than ever before. These closely packed components cause what is known as 'shadowing'. Shadowing is the phenomenon due to which closely packed components hinder the flow of cleaning medium, thereby, reducing cleaning effectiveness. As seen with Vicor boards, this close packing may influence cleaning to a great deal.

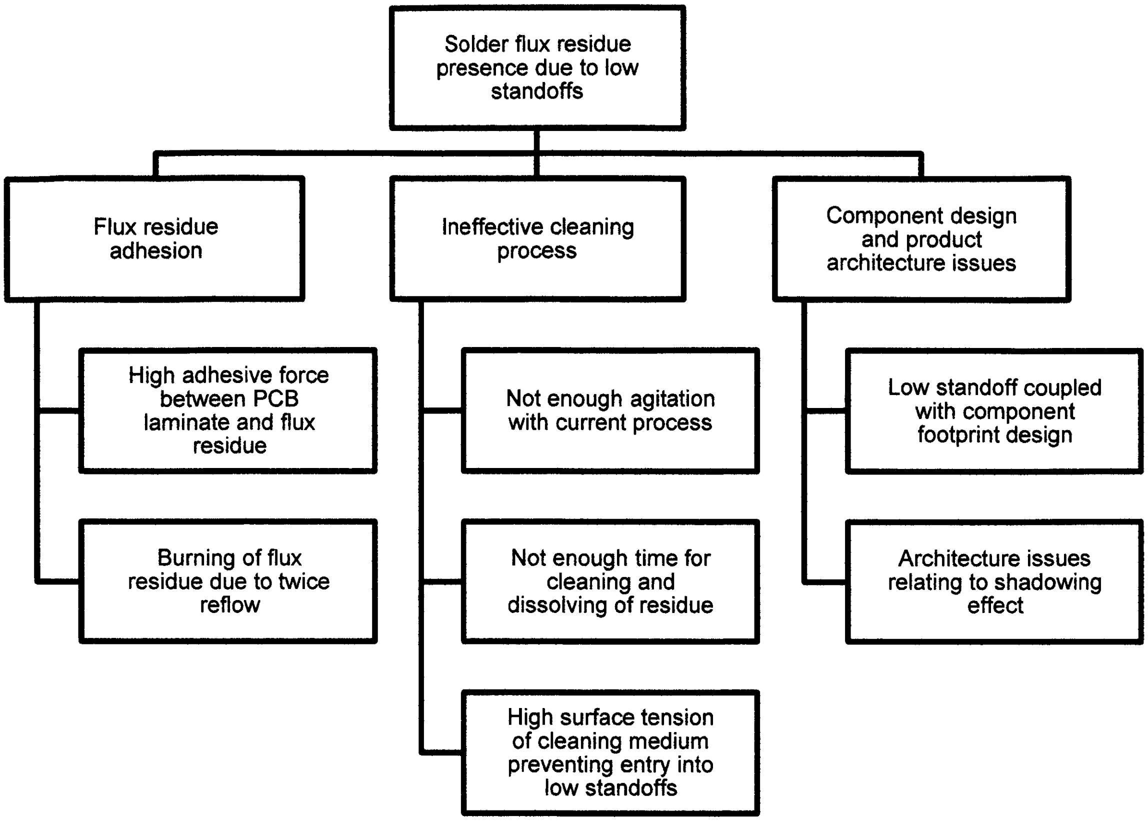


Fig. 5.1: Root cause hypotheses

5.3 Experiment Design for Hypotheses Testing

In Section 5.1, it has been seen that four main process variables qualify as process parameters, and can be varied to get the desired cleaning performance. Based on the hypotheses presented in Section 5.2, a set of experiments was designed to identify the root cause of the solder flux residue problem. The designed experiments required varying of the process parameters- agitation, chemical concentration, wash time and temperature. The object of the experimental study was to analyze the effect of parameters and their combinations on the cleaning performance. From these experiments, it would be possible to accept or reject the hypotheses presented earlier and identify the most probable causes of the flux residue problem.

5.3.1 Residue Adhesion Testing

The solder paste plays an important part in determining cleaning performance as its properties directly influence solubility and adhesion. It was earlier hypothesized that the sticking of residue to the PCB laminate, solder mask or copper pad was one of the reasons for poor cleaning. Thus, it was proposed that a soak cycle in water be added to the process, just before the centrifugal water wash. It was believed that the water would penetrate the standoffs, soften the residue and the subsequent centrifugal washing process would help lift off and dissolve the residue. Fig. 5.2 shows the process flow for the experiments.

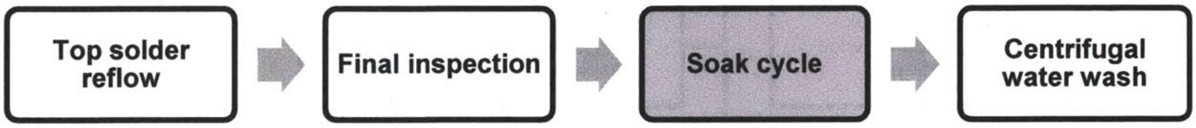


Fig. 5.2: Process flow for soak experiments

Another hypothesis was that the residue was getting burnt-in due to reflowing of the boards twice through the reflow oven. This would also contribute to increasing residue adhesion, thereby reducing cleaning performance. This supposition was made on the basis of visible brown residues in the preliminary visual inspections. Thus, it was proposed that the boards be washed after each reflow to avoid burning-in and see the cleaning performance. This has been shown in Fig. 5.3 below.

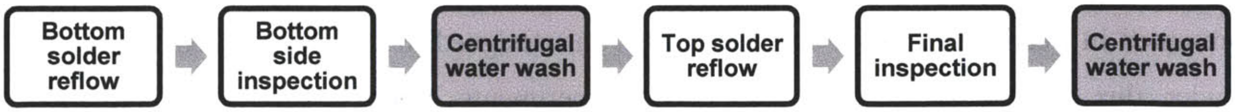


Fig. 5.3: Process flow for twice water wash experiments

5.3.2 Cleaning Ineffectiveness Testing

One of the major hypotheses is that with the current centrifugal water wash process, the agitation levels are not high enough for the water to enter the standoffs. To test this, it was proposed that the boards be subjected to an ultrasonic cycle in a water bath prior to the centrifugal cleaning. This was done as previous work mentioned in Chapter 4 indicates that ultrasonic cleaning offers higher levels of agitation and also improves cleaning performance. The process flow for these experiments was similar to the soak experiments and is shown in Fig. 5.4.

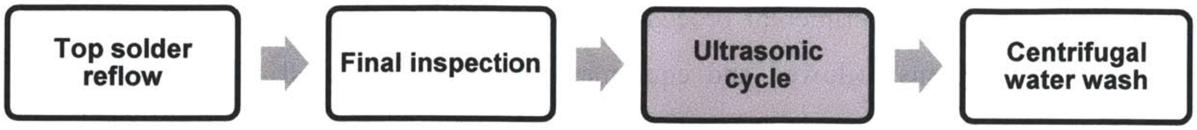


Fig. 5.4: Process flow for ultrasonic experiments

The hypothesis of insufficient amount of cleaning time with the current process was tested using the soak and ultrasonic cycle additions proposed above. The added process would give the cleaning more time than the current process. Furthermore, to test the effect of time on the cleaning performance, it was proposed that the soak and ultrasonic times be varied. Keeping the current washing time of 10 minutes as the baseline, the time for soak was varied between 5 and 60 minutes and for ultrasonic trials it was varied between 2 and 20 minutes.

The third hypothesis in this category deals with the effect of surface tension of the cleaning medium. Plain DI water, which is used currently, has high surface tension and does not allow effective cleaning. Thus, it was proposed to add a chemical agent to the soak and ultrasonic baths. The chemical would act as a surfactant and reduce the surface tension of the cleaning medium. This would allow the medium to enter the standoffs easily and dissolve the flux residues. Chemical agents from two vendors- Vendor A and Vendor B- were tested to determine their effect on cleaning.

5.3.3 Design and Architecture Testing

One of the major concerns was the low standoffs, which hinder proper cleaning. These standoffs depend on the component architecture and footprint design. Any layer of material which reduces standoff may inhibit cleaning, as may improper flow channels under the components. To test this hypothesis, it was proposed that two kinds of components be analyzed each for the MLP FETs and the chip capacitors. These components had similar standoffs, but different architectures or footprint designs.

5.4 Experimentation Methodology

In this section, the methodology is explained with respect to experimental procedures and analysis methods. The experimental procedure deals with the details of the experiments, test boards, procedural steps followed and equipment and apparatus used. The analysis method details the approach to inspecting the test boards after experimentation.

5.4.1 List of Experiments

The levels for the process parameters for the various experiments are shown in Table 5.1 below.

Table 5.1: Factor levels used for experiments

Parameter	Factor Levels
Agitation	Soak, Ultrasonic, Centrifugal
Chemical Concentration	7.5%
Chemicals Used	A, B
Time (min)	2, 5, 10, 20
Process Temperature (°C)	60, 70

Based on the proposed experimentation in Section 5.3, the following table of experiments was drawn up:

Table 5.2: List of experiments

	S. No.	Board No.	Agitation	Chemical Conc. (by volume)	Time (min)	Temp (°C)
Phase 1: RC-1	1	56	Centrifugal - Baseline	N/A	10	60-65
	2	35	Twice water washed	0	10	60-65
	3	36	Twice water washed	0	10	60-65
	4	40	Soak	0	5	60
	5	41	Soak	0	10	60
	6	42	Soak	0	20	60
	7	43	Soak	7.5% Chemical A	5	60
	8	44	Soak	7.5% Chemical A	10	60
	9	45	Soak	7.5% Chemical A	20	60
	10	46	Soak	7.5% Chemical B	10	60
	11	47	Ultrasonic	7.5% Chemical B	5	60
	12	52	Ultrasonic	0	5	60
	13	53	Ultrasonic	0	10	60
	14	54	Ultrasonic	7.5% Chemical A	5	60

	15	55	Ultrasonic	7.5% Chemical A	10	60
	16	57	Soak	0	40	60
	17	58	Soak	0	60	60
Phase 2: **RC-1**	18	48	Soak	0	60	60
	19	405	Ultrasonic	0	2	60
	20	406	Ultrasonic	0	10	60
	21	407	Ultrasonic	0	20	60
	22	409	Soak	7.5% Chemical B	10	60
	23	410	Soak	7.5% Chemical B	10	70
	24	411	Soak	7.5% Chemical A	10	60
	25	412	Ultrasonic	7.5% Chemical B	5	60
	26	413	Ultrasonic	7.5% Chemical A	5	60
	27	396	Centrifugal	7.5%	10	60-65
	28	397	Centrifugal	7.5%	10	60-65
	29	399	Centrifugal	10%	10	60-65
	30	400	Centrifugal	10%	10	60-65
	31	401	Centrifugal	12.5%	10	60-65
	32	402	Centrifugal	12.5%	10	60-65
	33	403	Centrifugal	5%	10	60-65
	34	404	Centrifugal	5%	10	60-65
Phase 3: **RC-2**	35	680	Centrifugal - Baseline	N/A	10	60-65
	36	681	Ultrasonic	0	5	60
	37	682	Soak	7.5% Chemical B	10	60
	38	683	Ultrasonic	7.5% Chemical B	5	60

As seen above, the experiments were conducted in three phases. The first phase consisted of the soak/ultrasonic experiments and the twice water wash experiments. The second phase included some experiments which were repeated so as to gauge repeatability of the results. Also included in the second phase were the extra ultrasonic experiments to obtain data points for 2 and 20 minutes and centrifugal experiments with varying chemical concentrations. The third phase of experiments was done with a different test board for design and architecture testing.

5.4.2 Test Boards

To derive meaningful results from the experiments, it was required that a test board be chosen which contains components with low standoffs so that the cleaning performance for a pessimistic case can be gauged. Another requirement was that the test board must contain different types of components. Therefore, a product, RC-1, meeting these requirements was chosen as the test board for Phase 1 and Phase 2 experiments. RC-1 has 16 modules, each having a top and a bottom side. The components on it range from MLP FETs to chip capacitors, resistors and chip-scale packages (CSP), with standoffs as low as 50 μm. The MLP FET in RC-1 is a dual-leg FET which can be seen in Fig. 5.5. The test board is shown in Fig. 5.6.

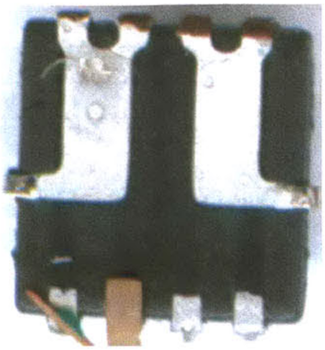
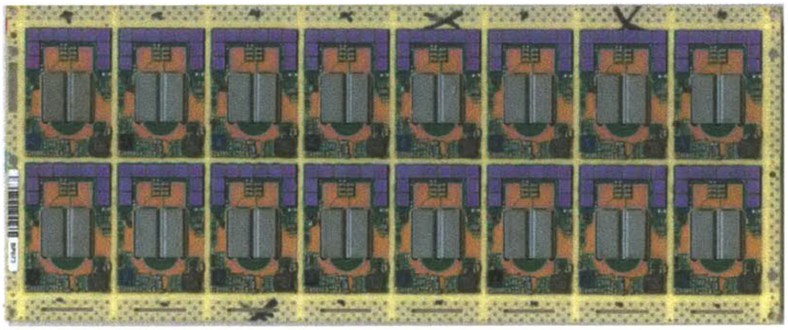
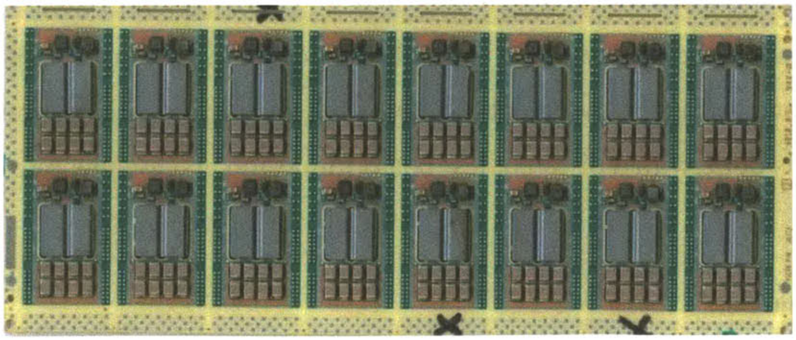


Fig. 5.5: Dual-leg MLP FET



(a) Top Side



(b) Bottom Side

Fig. 5.6: Test board – RC-1

For Phase 3 experiments, the objective was to test for component design issues which may influence cleaning performance. Thus, a test board, RC-2, was chosen which contained MLP

FETs which were single-leg as opposed to the dual-leg FETs in RC-1,both having similar standoffs. The single-leg FET is shown in Fig. 5.7 and the test board RC-2 in Fig. 5.8.

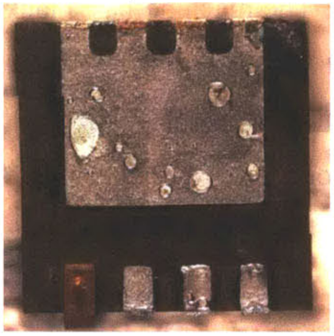
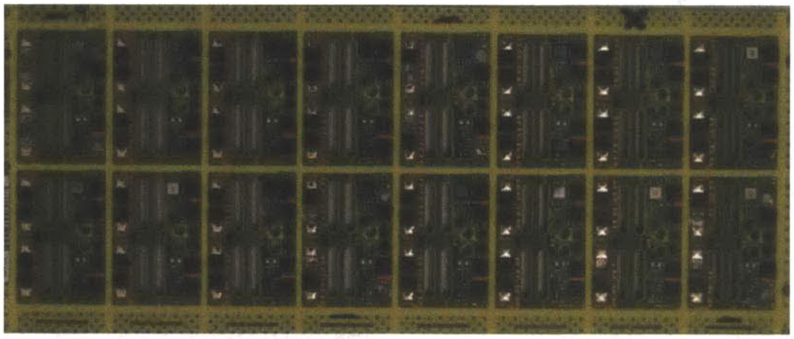
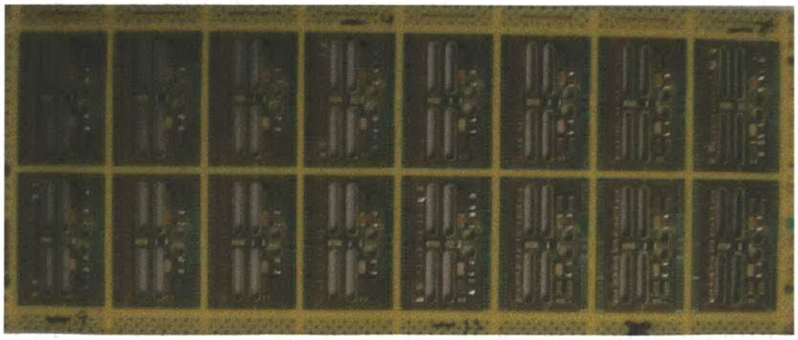


Fig. 5.7: Single-leg MLP FET



(a) Top Side



(b) Bottom Side

Fig. 5.8: Test board – RC-2

5.4.3 Experimental Setup and Procedure

To conduct the experiments, a Cole-Parmer 8893 small ultrasonic cleaning machine was chosen, which is shown in Fig. 5.9. The machine has a tank volume of approximately 9.5 liters and was used for the soak as well as ultrasonic experiments due to sufficient tank capacity required to soak the boards. The machine has the ability to heat the bath up to a temperature of 69°C and create ultrasonic vibrations with a frequency of 42 kHz. For trials with chemical agents, the solution was first heated and then degassed using the degassing option to make the concentration uniform and to expel any gas bubbles formed during heating. The test board was placed on an aluminum carrier, which was then immersed in the water or chemical solution bath. As described earlier, each trial was followed immediately by the centrifugal water wash process.

Fig. 5.9: Cole-Parmer 8893 ultrasonic cleaner

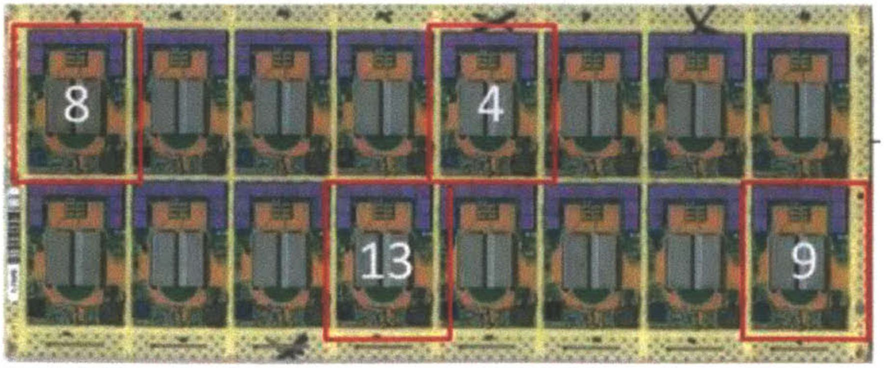
5.4.4 Analysis and Inspection Procedure

To understand flux residue distribution on boards, it was found that the chemical-electrical methods of cleanliness testing mentioned in Chapter 2 were not suitable for the analysis of boards after the experiments. Thus, visual inspection was chosen as the primary method of analysis. After the centrifugal water wash, boards were left to dry for at least 20 hours before inspection.

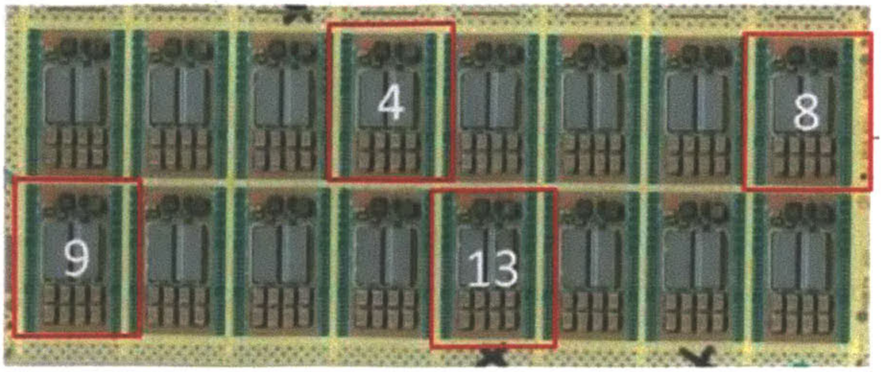
To inspect for presence of flux residue, components from the boards were pried off using a flat marking chisel and a small ball peen hammer. The pried off components were stored for inspection. To support the board, a standard vice was used. For the visual inspection, a two-pronged approach was followed. After prying off the components, first the boards were analyzed at the component footprints under the microscope to check for residue presence. Next, the individual components were analyzed on their undersides under the microscope. This way, any transfer of residue from board to component or vice versa would be detected. The magnification used for visual inspection was 50X, and 100X was used for finer viewing.

5.4.4.1 Visual Inspection Methodology

To obtain a representative picture of the cleaning performance, 4 modules out of a total of 16 from each board were chosen for inspection. As depicted in Fig. 5.10, module numbers 4, 8, 9 and 13 were selected; this was done for both test boards RC-1 and RC-2. This staggered method of selection of modules was chosen to ensure that each region of the board is sufficiently accounted for and spatial variations, if any, would be noticed. Each module had a number of different types of components. Thus, all major component types were selected as shown in Fig. 5.11 for RC-1 and RC-2. Table 5.3 and Table 5.4 list the components selected for both test boards.

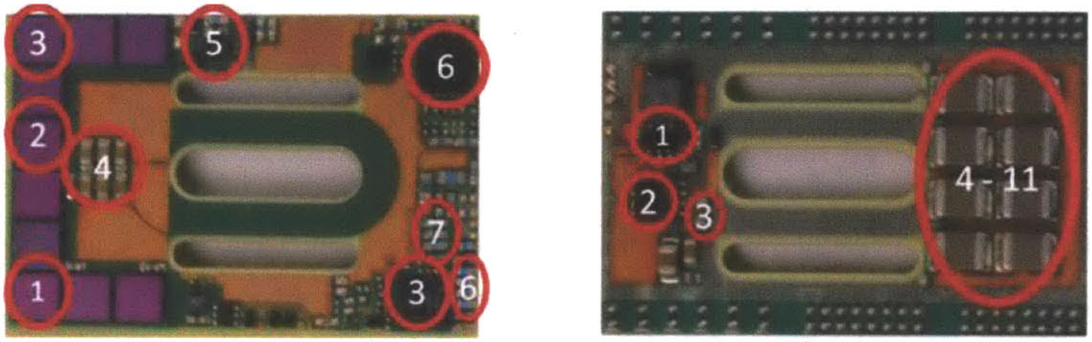


(a) Top Side

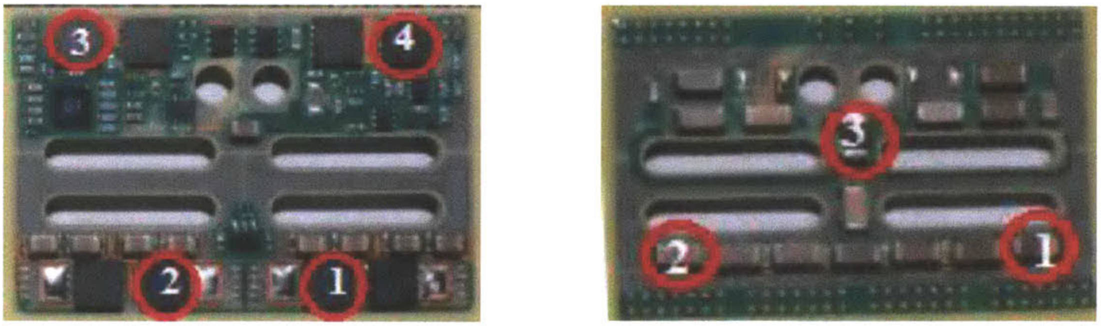


(b) Bottom Side

Fig. 5.10: Modules selected for inspection



(a) RC-1 Top Side (b) RC-1 Bottom Side



(c) RC-2 Top Side (d) RC-2 Bottom Side

Fig. 5.11: Components selected for inspection

Table 5.3: List of components selected for inspection in RC-1

	Component No.	Component Type
TOP SIDE	1-3	BGA FET
	4	0603 chip capacitors
	5	Common mode choke
	6	MLP Controller
	7	0201 chip capacitors
	8	Chip resistors
	9	CSP
BOTTOM SIDE	1	FET
	2	Dual-leg MLP FET
	3	0603 chip capacitor
	4-11	1210 chip capacitors

Table 5.4: List of components selected for inspection in RC-2

	Component No.	Component Type
TOP SIDE	1-3	Single-leg MLP FET
BOTTOM SIDE	1-2	1206 chip capacitors
	3	1207 chip capacitors

5.4.4.2 Cleaning Performance Metric

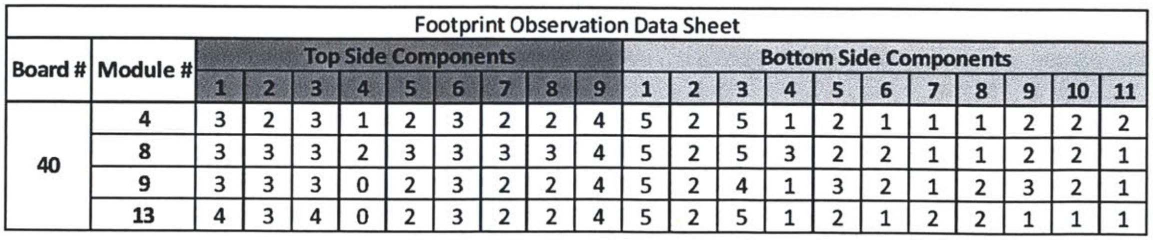
For visual inspection of the boards, it was essential to develop a method to define cleaning performance for each trial depending on the amount of flux residue observed. In Chapter 4, previous cleaning studies have made use of a few different approaches. One method can be extremely qualitative in which residue presence is indicated by a yes/no. This is essentially a Go/No Go type of analysis. However, it was found that this method does not specifically indicate residue distribution on boards and underneath components, nor the intensity of residue presence. Besides, this approach does not provide for a quantitative method to define cleaning performance. Another method, which is a more quantitative approach evolving from the previous method, uses a percentage cleaning efficiency metric. Here the cleaning efficiency is calculated as a ratio of completely clean components to total components. Although this method introduces a numeric quantity and builds upon the numeric metric drawback, it suffers from other limitations of the previous method. Thus, it was required that a new method of cleanliness performance be defined which provides for:

1. quantitative assessment of flux residue intensity
2. distribution analysis of flux residue, and,
3. acceptable inspection reproducibility

In view of the above requirements, a six-point grading system, shown in Table 5.5, with integer scores ranging from 0 to 5 was proposed. Here, 0 indicates large amounts of flux residue and 5 indicates completely clean. This developed scheme was an improvement over a similar scheme used by Lee and Bixenman in their research [10], which defines cleaning performance on a five-point scale ranging from no cleaning, significant residue, medium residue, low residue and completely clean. Their approach would not be suited here as components being tested have different footprints, rendering the flux distribution distinct for each component. As each component had a different distribution of residue, the grading scheme used in this work was adapted for each component. This metric was used for both component footprint observations on the boards as well as for component underside observations. A sample observation data sheet is shown in Fig. 5.12.

Table 5.5: Grading scheme

Cleaning Performance Metric	
Score	**Description**
5	Completely clean
4	Trace or minute amounts of residue
3	Low flux residue incidence
2	Non-uniform residue presence
1	Uniform residue presence
0	Large amounts of residue



Footprint Observation Data Sheet

Board #	Module #	Top Side Components									Bottom Side Components										
		1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	11
40	4	3	2	3	1	2	3	2	2	4	5	2	5	1	2	1	1	1	2	2	2
	8	3	3	3	2	3	3	3	3	4	5	2	5	3	2	2	1	1	2	2	1
	9	3	3	3	0	2	3	2	2	4	5	2	4	1	3	2	1	2	3	2	1
	13	4	3	4	0	2	3	2	2	4	5	2	5	1	2	1	2	2	1	1	1

Fig. 5.12: Sample observation data sheet

As mentioned earlier, each component had different distribution and patterns of flux residue incidence. This was particularly observed in the case of component undersides. Thus, the grading scheme mentioned was adapted and defined for each type of component. However, the grading scheme for two types of components – the MLP FETs and 1210 chip capacitors- were most distinct than the rest due to lower standoffs and, thus, higher amounts of residue. It is important to note that flux distribution for component footprints was dissimilar to that for component undersides and, therefore, they required different grading patterns. Sample grading schemes for the two components mentioned above are shown in Fig. 5.13 and Fig. 5.14.

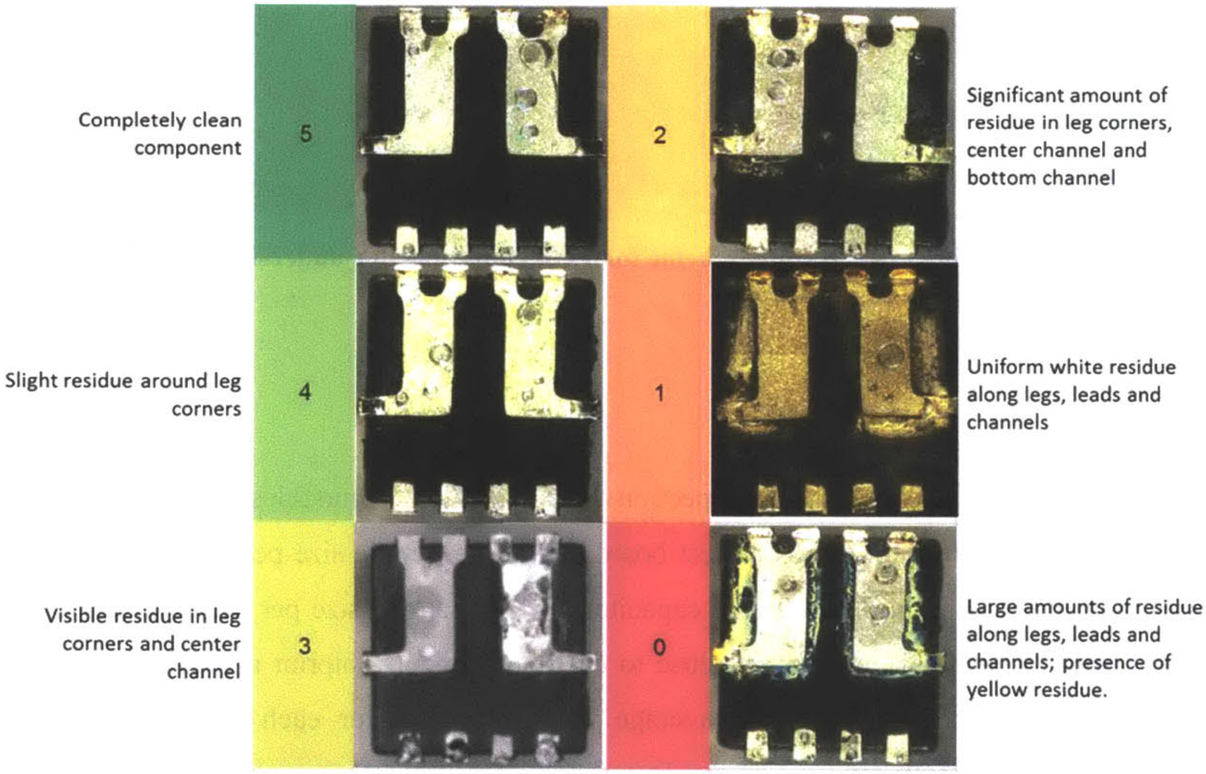


Fig. 5.13: Grading scheme for MLP FET underside

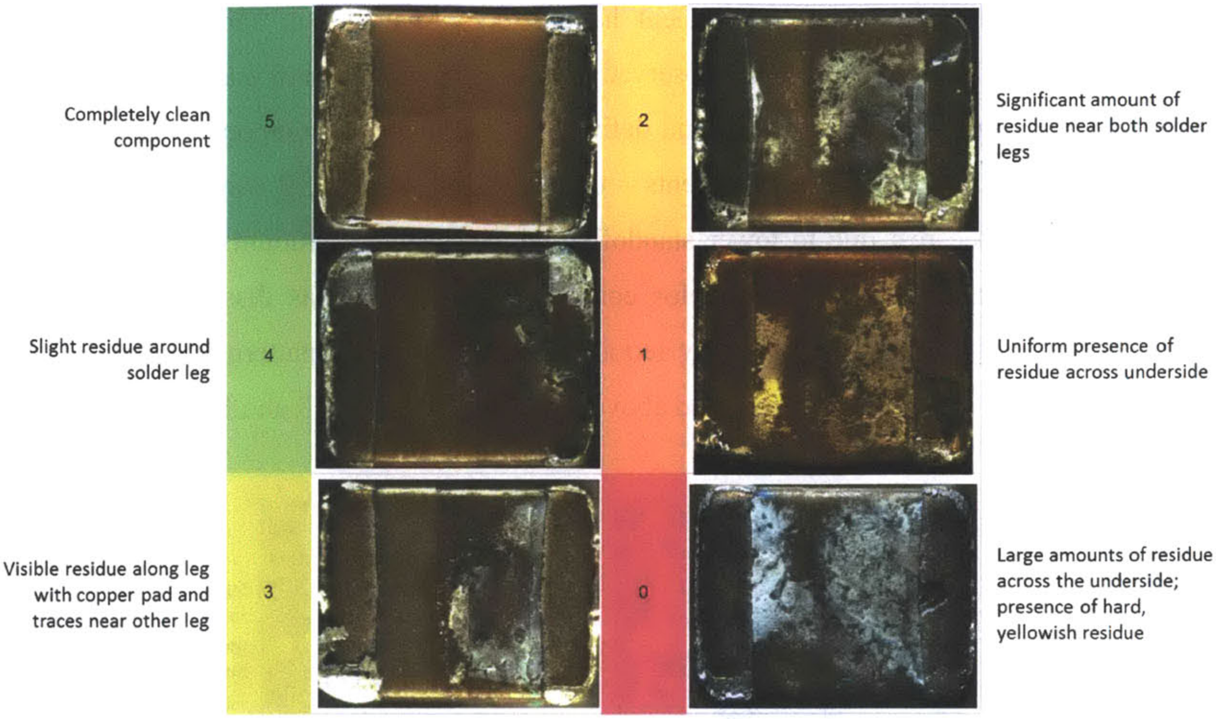


Fig. 5.14: Grading scheme for 1210 chip capacitor underside

5.5 Data Analysis

As explained above, visual inspection was done on 4 modules per board and 20 components per module for the RC-1 test board. Thus, the sample size per component per trial was 4, with the exception of 1210 chip capacitors, whose sample size per trial was 8. After the visual inspection and assigning of a metric to each component footprint and underside, a total cleaning performance metric, called average cleaning score, for each trial was calculated according to Eq. 1 as follows:

$$Average\ Cleaning\ Score = \frac{\sum_1^n(Cleaning\ Metric)}{n} \tag{1}$$

where, n is the total number of components analyzed.

The above approach was used in many trials, but it was consistently observed that certain components were always clean (score of 5), whereas others with lower standoffs, such as MLP FETs and 1210 chip capacitors, were not. This was leading to incorrect cleaning performance metrics for the trials in whole, as the process of averaging diluted the cleaning score. Thus, it was proposed that for data analysis, the average cleaning score would just be an average of scores of those components which were consistently not clean, viz., the MLP FET and 1210 chip capacitors. Based on these average scores, the plots of cleaning performance versus the process parameters were made, to observe trends and effects of parameter variation.

As mentioned in Section 5.4.4.2, one of the criteria to choose a grading system was the reproducibility of the inspection results. As the visual inspection was done by more than one inspector and the grading scheme is not quantitatively defined, it was required to assess the accuracy of the observations of different inspectors. To achieve this, a Gauge Repeatability and Reproducibility (Gauge R&R) study was done on the observations of two different inspectors. The methodology and results of this study have been mentioned in Mukherjee's work [1]. Results of the Gauge R&R study showed that the variation in inspector observations was within acceptable limits. This result showed that the developed grading scheme was acceptable with regards to reproducibility.

Chapter 6 — Results and Discussion

6. Introduction

This chapter presents the results of the experiments mentioned in the previous chapter. The results presented show the variation of the cleaning performance with varying process conditions. A comparative study of the different experiments has also been included. Based on the results, a discussion on the root cause hypotheses has been presented.

6.1 Experiment Result Analysis

As mentioned in the previous chapter, the main goal of the experiments conducted was to accept or reject the root cause hypotheses. To achieve this, the experiments were designed such that parameters such as time, agitation and chemical concentration are varied one at a time. This would help in correctly understanding the reasons for flux residue incidence. In this section, the variation of cleaning performance with varying parameters has been shown. Also included in this section are the results of other experiments such as centrifugal water wash after every reflow and Phase 3 experiments.

6.1.1 Effect of Agitation

In the experiments conducted in Phases 1 and 2, 13 boards were subjected to soak before centrifugal cleaning, which includes 6 boards in DI water and 7 boards in 7.5% chemical solution of either Chemical A or B. 10 boards were subjected to an ultrasonic cleaning cycle before the centrifugal cleaning, with 5 boards each in DI water and chemical solution. Results indicate that introduction of both, the soak and ultrasonic cycles, improved cleaning performance when compared to the baseline cleaning performance. However, the improvement shown with ultrasonic cleaning was much higher than that of soak, which may be due to higher amounts agitation. Table 6.1 shows the average cleaning performance for soak and ultrasonic cycle addition for all times, which is also represented graphically in Fig. 6.1.

Table 6.1: Effect of agitation

Agitation Type	Cleaning Medium	Avg. Cleaning Score
Soak	DI water	1.6
Soak	7.5% Chemical A or B	3.4
Ultrasonic	DI water	4.7
Ultrasonic	7.5% Chemical A or B	4.9

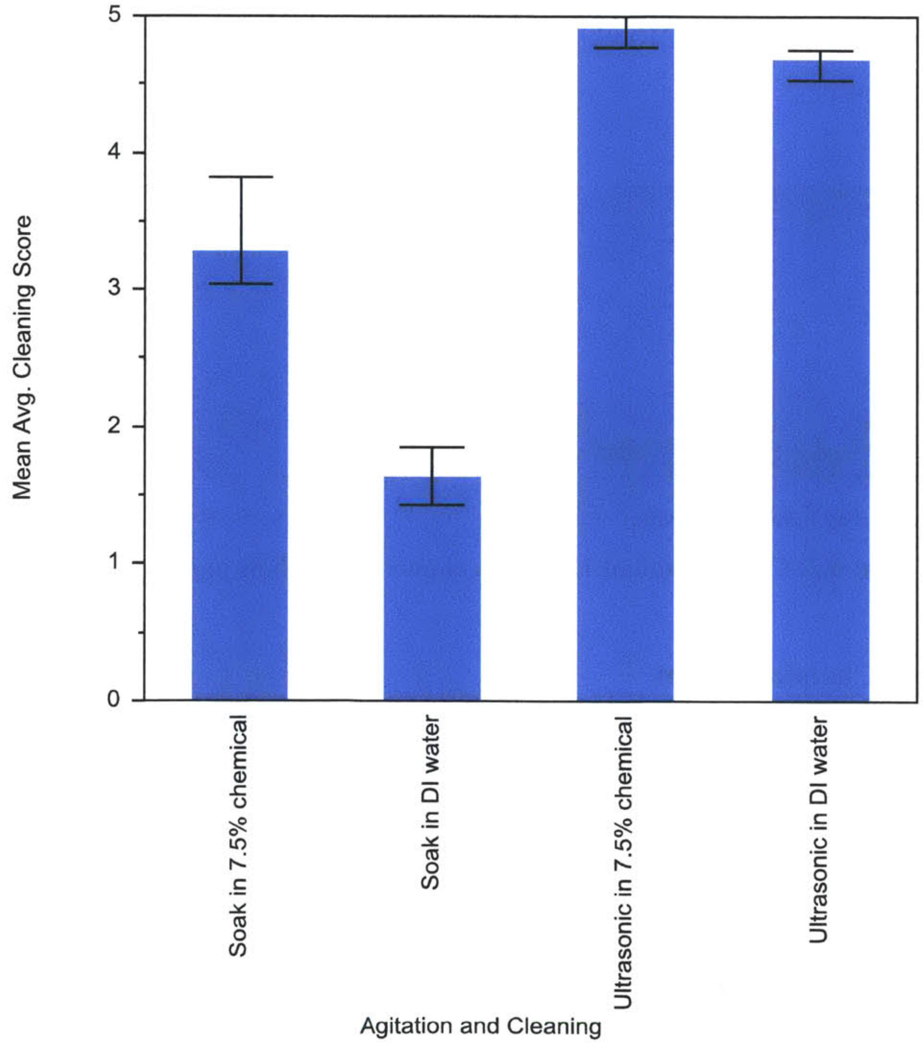
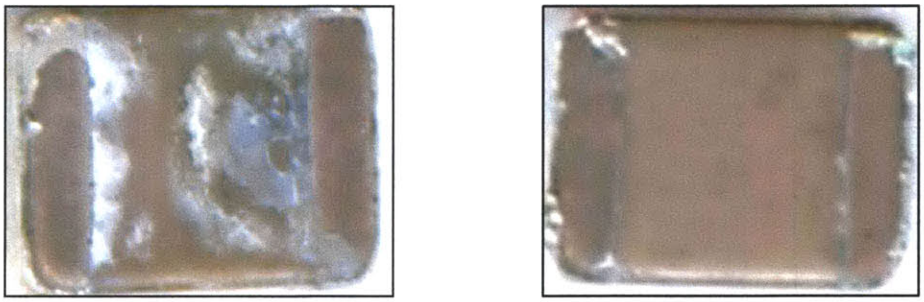


Fig. 6.1: Effect of agitation

From the results above, it is clear that agitation is an important factor in determining the cleaning performance. The primary reason for this is the low standoffs which require the cleaning fluid to be forced in with more energy to achieve effective cleaning. Another reason could be the ability of the cleaning medium to easily loosen the residue off the PCB surface and components due to higher agitation. It can be noted from Fig. 6.1 that for the same cleaning medium, the improvement in cleaning performance is high when ultrasonic cleaning is used. Another important observation was that the difference in cleaning effectiveness in ultrasonic trials with water and chemical was small. Thus, it was concluded that the cleaning response to agitation is higher than to chemical concentration. It was also observed that the MLP FETs and the 1210 chip capacitors were mostly clean for ultrasonic trials. This can be seen from Fig. 6.2 which shows a comparison of 1210 chip capacitors for soak and ultrasonic trials with DI water and a time of 5 minutes.



(a) Soak in DI water (b) Ultrasonic with DI water

Fig. 6.2: Comparison of 1210 chip capacitors to show agitation effect

6.1.2 Effect of Chemical Agent

To understand the effect of chemical concentration, a total of 12 boards were trialed with chemical agents, which included soak as well as ultrasonic trials. For the purposes of evaluation, two kinds of chemical agents were used, Chemical A and Chemical B. These chemicals were primarily organic and alkaline in nature with constituents such as amines. Table 6.2 below provides a comparison of the average cleaning scores for all times for the two chemicals. The information above suggests that neither chemical agent is particularly better. However, it was seen that the performance of Chemical B was much better than Chemical A for soak trials. Also, Chemical A seemed to etch the copper pads of the boards, which may be due to its higher pH. It was, therefore, decided to use Chemical B for phase 3 and 4 experiments.

Table 6.2: Comparison of cleaning performances of Chemical A and Chemical B

Agitation Type	Cleaning Medium	Avg. Cleaning Score
Soak	7.5% Chemical A	3.1
Soak	7.5% Chemical B	3.8
Ultrasonic	7.5% Chemical A	5.0
Ultrasonic	7.5% Chemical B	4.8

From Fig. 6.1, it was seen that addition of chemical agent has a favorable effect on cleaning performance. For both soak and ultrasonic trials, the cleaning performance improved with the presence of chemical agent. As mentioned in Chapter 5, Phase 2 experiments also consisted of trials on the existing centrifugal machine with varying chemical concentrations from 5% to 12.5%. These experiments helped in determining the effect of chemical concentration with constant agitation. The results of the centrifugal trials have been summarized in Table 6.3 and Fig. 6.3.

Table 6.3: Effect of chemical concentration with centrifugal cleaning

Chemical Conc. (by volume)	Avg. Cleaning Score
5%	3.4
7.5%	3.9
10%	4.0
12.5%	4.4

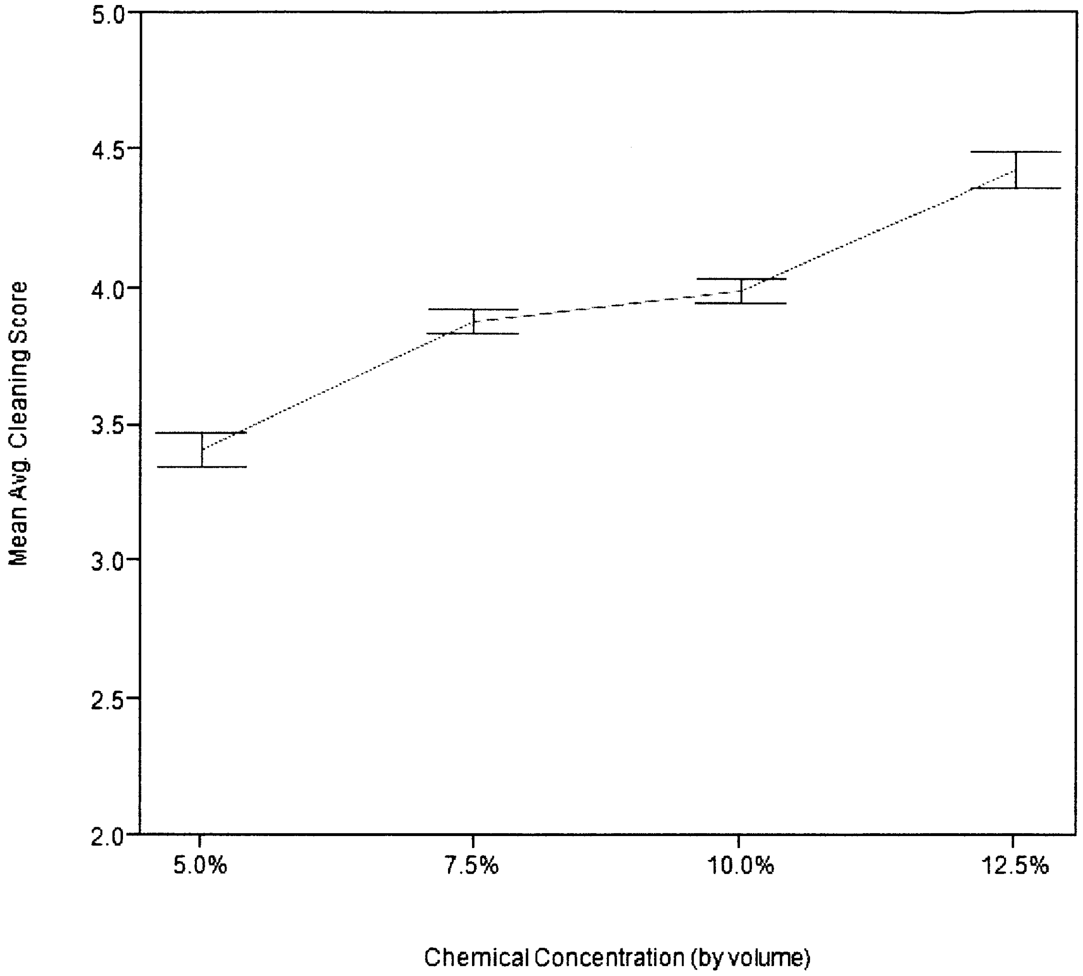
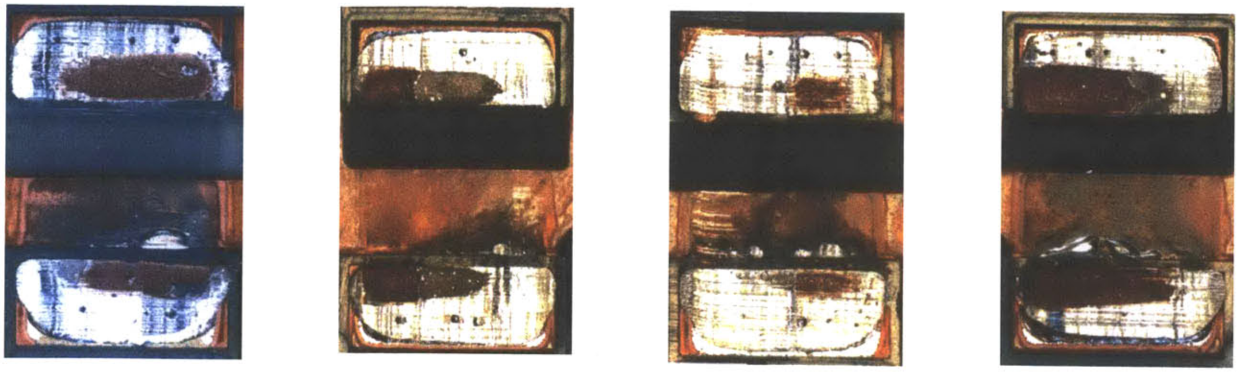


Fig. 6.3: Effect of chemical concentration with centrifugal cleaning

From the above results it can be seen that cleaning improves as concentration is increased. This is because with increasing concentration the surface tension of the cleaning medium reduces, thereby allowing easier entry into standoffs. It was also seen that although chemical concentration has a marked effect on cleaning performance, a large difference in cleaning under 1210 chip capacitors was not observed. Fig. 6.4 shows the effect of chemical concentration on 1210 capacitor footprint. It can be seen that a large amount of residue is still present on the copper pad.



(a) 5% (b) 7.5% (c) 10% (d) 12.5%

Fig. 6.4: Effect of chemical concentration on cleaning of 1210 chip capacitors

6.1.3 Effect of Soak and Ultrasonic Cleaning Time

In most of the experiments carried out, the soak time or the ultrasonic cleaning time was varied in order to understand the effect of time on cleaning performance. It was seen that cleaning performance improved as time was increased, but the amount of change was low. This indicates that although time has an effect on cleaning performance, the operating region, i.e., 5 minutes to 60 minutes, was above the region where time effects could be significant. Fig. 6.5 shows the comparison of soak and ultrasonic trials in DI water. Although no particular trend for soak trials can be observed, it was noted that longer soak times improved cleaning. An observation of particular importance here is that with ultrasonic cleaning in DI water, the average cleaning score seems to reach a saturation value between 10 and 20 minutes. This behavior indicates that the effect of cleaning time may not be large at large amounts of time. Also, the optimal level of time for this process would lie near the 'knee' of the curve, which occurs between 6 and 9 minutes.

Fig. 6.6 shows the comparison of soak and ultrasonic trials 7.5% chemical agent. It can be seen that the improvement in cleaning performance is more pronounced in soak experiments when time is increased. A significant observation from Fig. 6.6 is that for 10 minutes of ultrasonic cleaning with 7.5% chemical concentration, the cleaning score reaches 5. This indicates that ultrasonic cleaning with chemical agent can completely clean the flux residue.

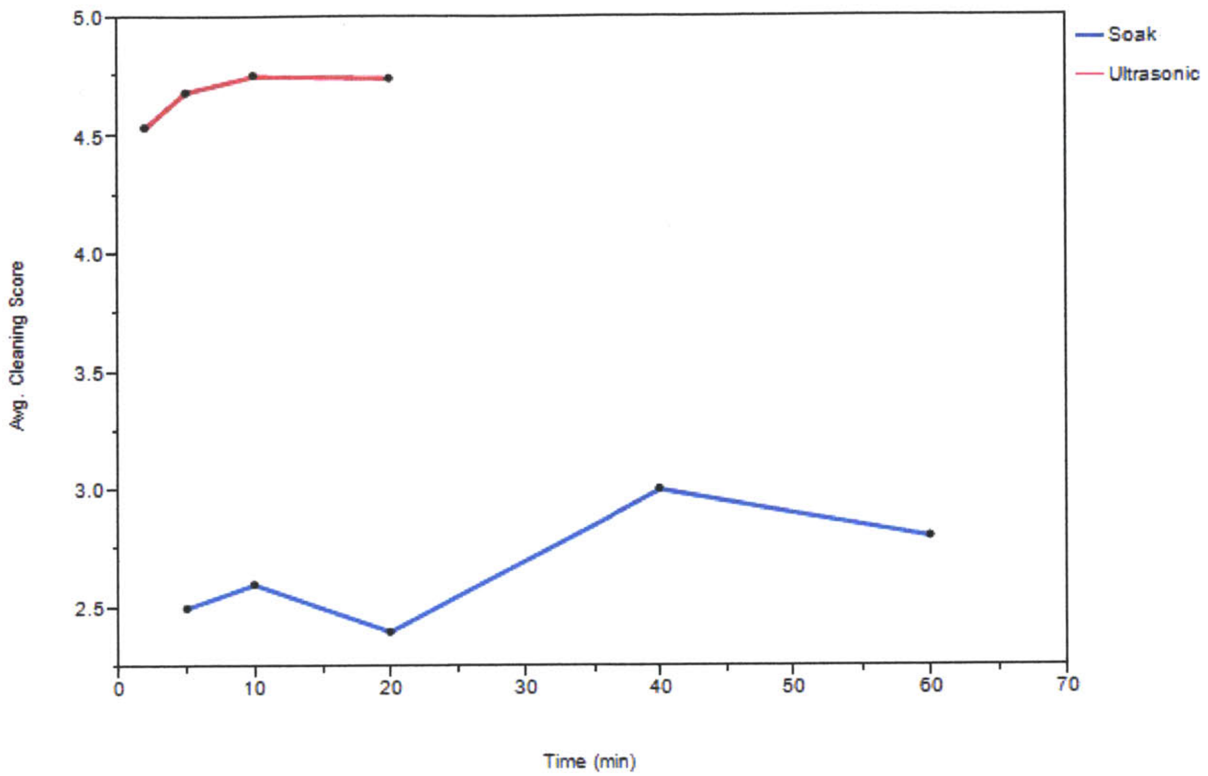


Fig. 6.5: Comparison of soak and ultrasonic trials in water

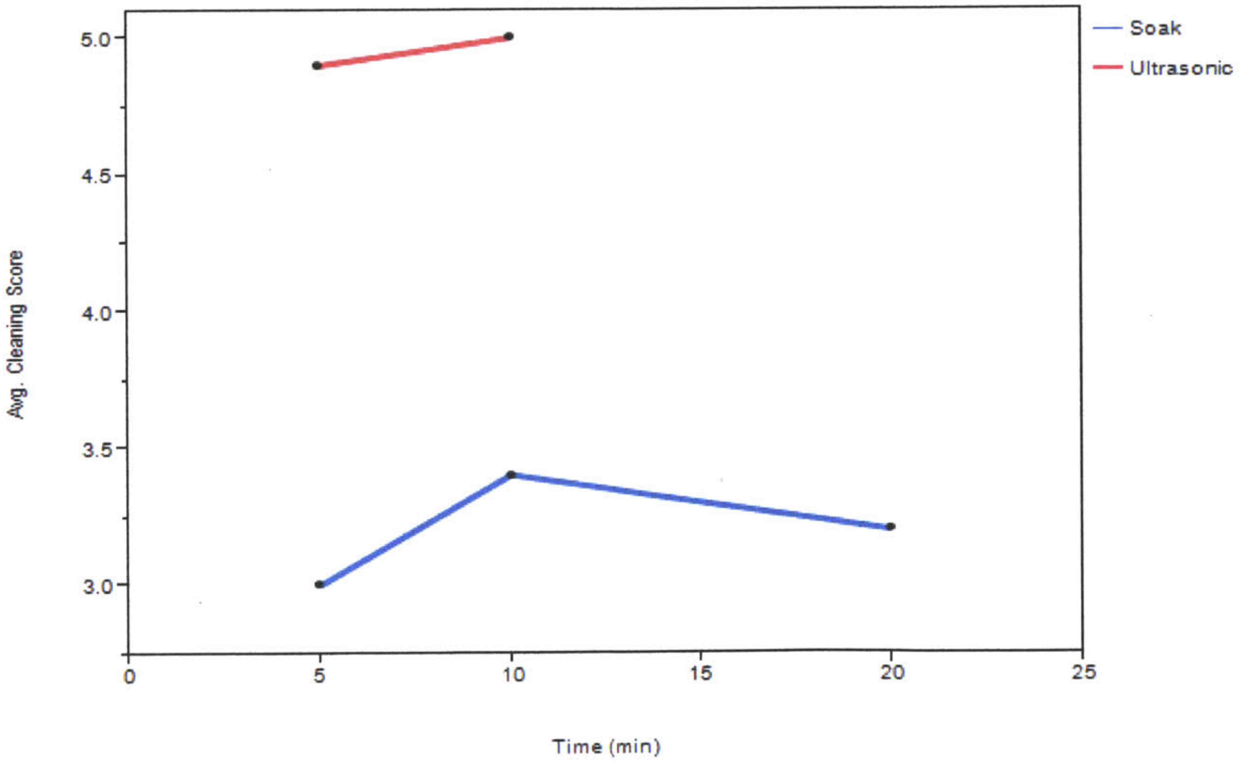


Fig. 6.6: Comparison of soak and ultrasonic trials in 7.5% chemical

6.1.4 Effect of Temperature

From previous research, it was concluded that higher temperature results in better cleaning. This was attributed to the reduced surface tension of the medium, improved solubility of the flux residue and increased activity of the chemical agent. Thus, most of the experiments were conducted at a high temperature of 60°C. However, to understand the effect of increasing temperature by 10°C, a soak experiment in 7.5% solution of Chemical B was conducted at 70°C. The average cleaning score for similar process parameters at 60°C was 3.81 and that at 70°C was 3.83. This was indicative of the fact that increasing the temperature has virtually no effect on cleaning performance at high temperatures. A similar conclusion to the effect of time can be drawn here, in that, beyond a threshold temperature, improvement in cleaning performance is much reduced.

6.1.5 Other Experiment Results

Besides the experiments in which parameter were varied, some other experiments were also done. One experiment was to test for burning-in of flux residue due to two reflows, by cleaning the test boards in the centrifugal washing machine after each reflow. The results for the two boards trialed show average cleaning scores of 1.53 and 1.56, respectively. These values were almost equal to the values of cleaning scores for the baseline process of a single centrifugal water wash. This result suggests that twice water washing did not improve cleanliness.

To study the effect of only ultrasonic cleaning, an additional experiment was conducted. The test board was RC-1 and the process parameters were 7.5% by volume of Chemical B and 5 minutes of wash time. Unlike the rest of the experiments, this process was not followed by a regular centrifugal water wash. It was found that the average cleaning score for this trial was 4.92, whereas for the trial with similar parameters and followed by centrifugal cleaning, the average score was 4.91. Thus, the cleaning performance in both cases was similar. This shows that ultrasonic agitation does not only force the cleaning medium under the low standoffs, but also helps to loosen and expel the residue from underneath components.

Phase 3 experiments were done to test design factors influencing cleaning. The experiments were conducted on RC-2, a different test board than the other experiments which used RC-1. It may be recalled, that RC-2 contains the single-leg MLP FET, whereas RC-1 contains the dual-leg MLP FET. It was postulated that the absence of a hindering center channel in the MLP FET in RC-2 would help improve cleaning performance. MLP FETs in RC-2 had predominantly brown, burnt-in residues when compared to RC-1 which had brown as well large amounts of white residues. The position of the brown residues under the MLP FETs in both test boards was similar – between the base legs and leads and along the leads. The white residues under the MLP FETs in RC-1 mainly occurred in between the dual legs and around them. Chip capacitors in RC-2 had residue only near the legs, unlike the RC-1, which had residue mostly in all areas. Fig. 6.7 provides a comparison of the MLP FET footprints in the two test boards.

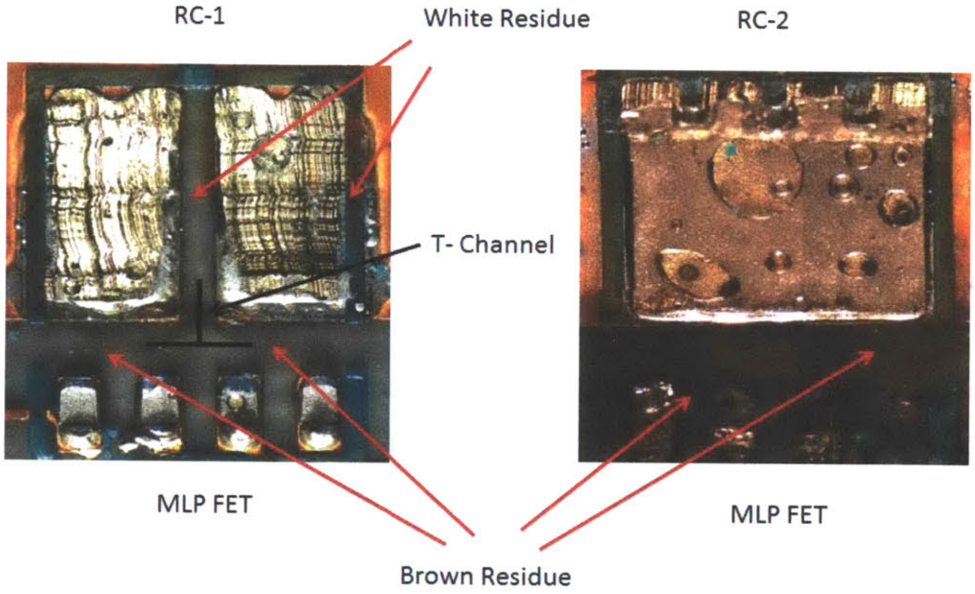


Fig. 6.7: Comparison of MLP FET in test boards RC-1 and RC-2

6.2 Discussion on Root Cause Hypotheses

Before experiments were conducted, it was postulated that the problem of flux residue incidence was due to certain reasons, which were mentioned in Section 5.2. The results of the experiments gave a lot of insight into the main causes of the residue presence. In this section, a discussion on validation or rejection of those hypotheses has been presented.

6.2.1 Flux Residue Adhesion

The first hypothesis was the adhesion of flux residue to the PCB laminate, solder mask and copper pads. This can be caused due to settling-in and sticking of the residue to the PCB, which may be further worsened by high reflow temperatures and reflowing the boards twice. This would also lead to burning-in of the residue. However, centrifugal water washes after each reflow showed that large amounts of residue were still present. This does not point to a rejection of the hypothesis, but is rather indicative of the fact that the baseline process is not effective enough to clean the boards. It has been well demonstrated by past researchers that the use of lead-free solder pastes and higher reflow temperatures can burn the residues causing high adhesion to the PCB laminate and other parts.

Interesting observations regarding residue adhesion come from the soak trials in which the boards were soaked in DI water and chemical baths followed by centrifugal cleaning. It was observed that the addition of soak cycle resulted in better cleaning performance. This can be attributed to the fact that the cleaning medium gets more time to enter the standoffs and moisten and loosen the residue in the soak cycle, which can be subsequently removed with ease in the centrifugal washing process. It was also seen that soak in chemical was more effective than soak in water, leading to the suggestion that the chemical can act on the residue with greater effect and can help dissolve the residue as well. However, addition of chemical agent to a soak bath did not greatly improve cleaning of the brown, burnt-in residues. Thus, on the whole, it was concluded that although adhesion of the flux residue to the PCB substrate and components takes place, it was not the major reason for poor cleaning performance.

6.2.2 Ineffective Cleaning Process

The second major hypothesis was that of an ineffective cleaning process relating to incorrect process parameters such as agitation and time. According to the proposed hypothesis, the baseline centrifugal water washing process does not create enough agitation for enough amount of time required for effective cleaning of the flux residue. This was also based on previous work carried out by chemical vendor companies for Vicor [14, 15], which showed that centrifugal cleaning results in poor cleaning when compared to other methods of cleaning.

The results of the ultrasonic experiments are of particular significance here, as they show the effect of improved agitation. From Fig. 6.1 it was seen that the high amount of increase in cleaning score from soak to ultrasonic indicates that increased agitation helps in better cleaning. Furthermore, it was found that with ultrasonic cleaning the brown, burnt-in residues were getting cleaned, which were not being removed with soak cycles in water or chemical. The ultrasonic cleaning provided sufficient agitation to enter, dissolve and flush out the residue from underneath components. Therefore, it was inferred that agitation is the main factor determining cleaning process performance.

Time, another factor deciding cleanliness, was seen to have a minor impact on cleaning performance. However, it must be noted here that the time factor used for the experiments was the time in excess of the baseline centrifugal process. The results discussed in Section 6.1.3 suggest that time may play an important role in deciding cleanliness when the region of operation is below the 'knee' of the curve. However, it will be incorrect to state that the cleaning process cannot be optimized in terms of time. This fact has been used by Mukherjee [1] to optimize a suitable cleaning process and by Rajendran [2] to analyze the systems performance of the selected cleaning process.

As mentioned in Section 6.1.2, addition of chemical agent to water showed a marked improvement in cleaning performance. Although, chemical agents act by loosening and dissolving the flux residue, their primary objective is providing easy access for the cleaning solution to the standoffs. This is achieved by reducing the surface tension of the cleaning medium. It was found that traces of the chemical solution were present underneath components for trials with chemical agent. These observations suggest that the chemical agent helped in delivering the solution under the components. Thus, it was shown that the centrifugal cleaning process with DI water was ineffective due to incorrect process parameters.

6.2.3 Component Design and Architectural Causes

To test for design and product architecture related causes, a few experiments with a different test board, RC-2, were conducted. The results of these experiments have been presented in Section 6.1.5. The results suggest that the component design greatly influences cleaning, which was noted by the large amounts of residue present underneath the dual-leg MLP FET as opposed to the single-leg MLP FET, which have similar standoffs. Thus, it was concluded that one of the major hindrances to cleaning the low standoff, dual-leg MLP FET is the presence of the T-channel underneath the component. This kind of design restricts the flow of cleaning medium below the component and does not let it effectively dissolve the residue. Thus, a single flow channel, as in the case of the single-leg MLP FET, would be beneficial to the cleaning process performance.

Besides the above results, Mukherjee has highlighted the variation of cleaning score with position of the 1210 chip capacitors found on the bottom side of the test board RC-1 [1]. Fig. 6.8 shows the arrangement of the capacitors. For this study, the centrifugal cleaning trials from Phase 2 experiments were used. The mean and standard deviations of the scores for each capacitor were calculated across the four modules. The results have been presented in Table 6.4, which indicate that the cluster of four capacitors in the center was less clean than the outer cluster in all cases. These observations can be explained by the shadowing effect of the outer capacitors on the inner capacitors.

Another important observation throughout the course of the study was that there was residue presence, often burnt-in, on the copper pad underneath the 1210 chip capacitors footprint and on the underside of the capacitors. This can be attributed to the fact that the copper pads below the chip capacitors reduce the available standoff, leading to ineffective cleaning and burning-in of the residue. Thus, it can be concluded from the above that component design and product architecture play a key role in deciding product cleanability.

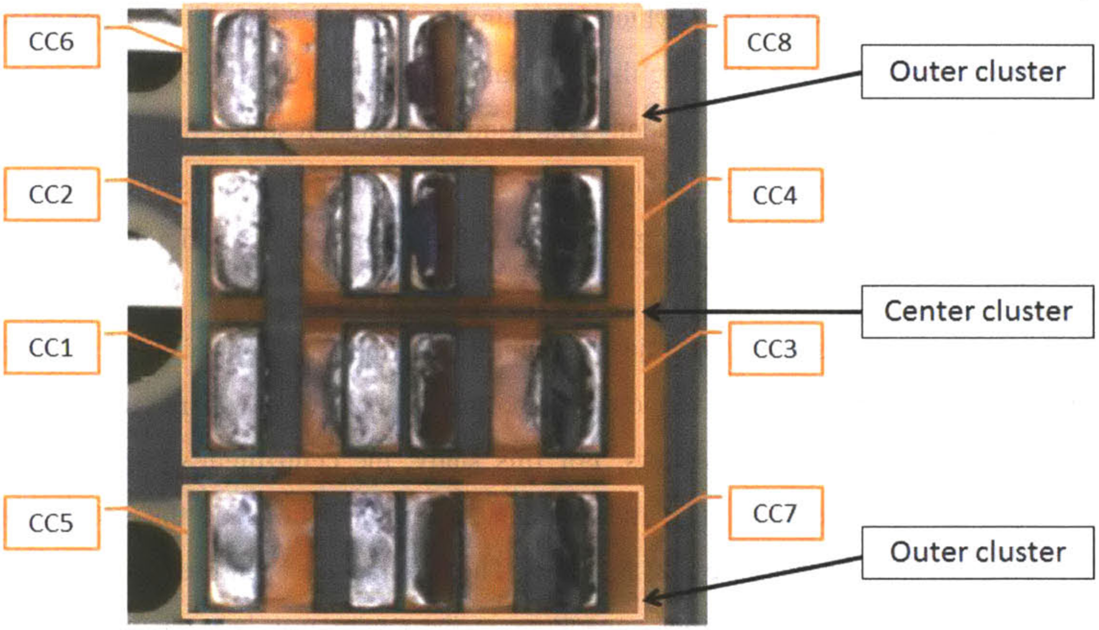


Fig. 6.8: Footprint of 1210 chip capacitor array [1]

Table 6.4: Variation of cleaning score of 1210 chip capacitors [1]

Component	Mean	Std. Dev.
CC1	3.8	0.38
CC2	3.7	0.39
CC3	3.8	0.44
CC4	3.8	0.34
CC5	4.0	0.49
CC6	4.1	0.31
CC7	4.2	0.40
CC8	4.1	0.38

Chapter 7 — Conclusions and Future Work

7. Introduction

The previous two chapters detailed the research methodology and results. In this chapter, the initial part contains the summary of the work done and the conclusions drawn from the results. The final part of this chapter lays out the recommendations to improve product cleaning at Vicor and the future work which can be carried out in this field to improve cleaning process performance.

7.1 Summary and Conclusions

The motivation for the study carried out was the incidence of solder flux residue underneath the components on boards manufactured by Vicor. To understand the problem, a set of hypotheses for root cause identification were put forward. These hypotheses were based on the product architecture, which includes low standoffs, previous research and work done in the field of post-SMTP cleaning. To validate the hypotheses, experiments spanning over three phases were conducted. The experiments consisted of addition of soak cycle and ultrasonic cycle before the centrifugal cleaning process. The results of these experiments gave vital information regarding the influence of agitation, cleaning agent, time, temperature and product design on cleaning performance. It was found that agitation is the most critical factor determining cleaning performance followed by product design, chemical agent and time. A comparison of all the cleaning methods and experiments is shown in Fig. 7.1. It was found that ultrasonic cleaning in a chemical bath consistently provides the best cleaning performance.

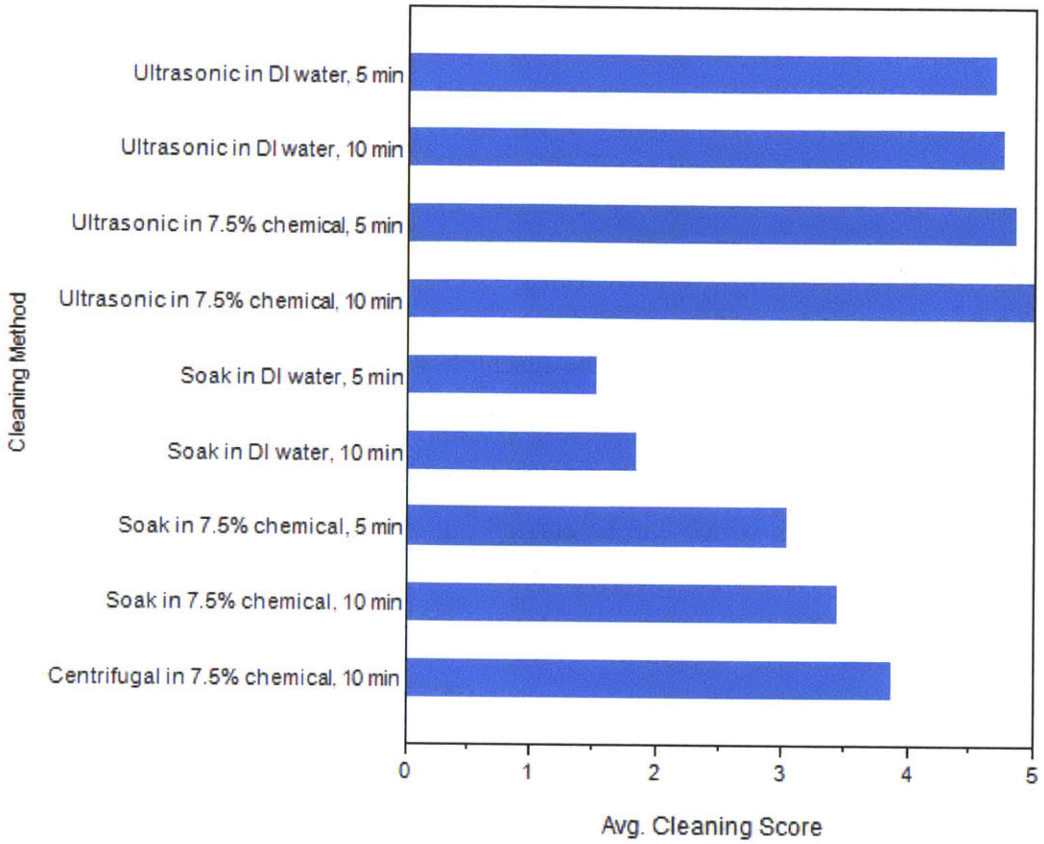


Fig. 7.1: Performance summary of cleaning alternatives

Based on the experiment results mentioned in Chapter 6, the root causes of the flux residue incidence problem were identified and the following conclusions were drawn:

1. It was concluded that the flux residue was getting burnt-in which adhered to the PCB substrate and was difficult to remove. However, this was not a major reason for poor cleaning performance.
2. The inability of the current centrifugal cleaning process in DI water to effectively clean low standoffs was primarily due to the failure of the centrifugal machine to provide enough force to deliver the cleaning medium. The ultrasonic cleaning trial without a subsequent centrifugal water wash shows that the centrifugal process is ineffective in expelling and dissolving the flux residue from underneath components. Thus, a low agitation level with centrifugal cleaning was the main cause of flux residue incidence.

3. The addition of chemical agent influenced cleaning by reducing the surface tension of the cleaning medium and by aiding the process of residue dissolution. It was concluded that the high surface tension of DI water prevented it from easily accessing the standoffs. The addition of chemical agent can be construed as an aid to counter an ineffective cleaning process. A cleaning process with high agitation and time would not require cleaning agent for effective cleaning.
4. Longer cleaning times were found to aid cleaning performance. However, the effect observed was not large. This suggested that less time for cleaning was not a primary reason for ineffective cleaning.
5. Design and architectural issues greatly influenced product cleanability. If design and architecture rules are modified to provide enough standoff, then, the use of chemical agent can be greatly reduced.

On the basis of these conclusions, a set of recommendations have been provided in the following section in order to determine the best cleaning alternative.

7.2 Recommendations

The following recommendations and suggestions are offered to Vicor to improve the post-SMTP flux residue cleaning process:

1. It is recommended that a batch-type ultrasonic cleaning process be adopted in place of the current centrifugal cleaning process.
2. The use of chemical agent in ultrasonic cleaning can give extremely good cleaning results for the existing product design. Thus, the use of chemical agent is suggested in the ultrasonic process, followed by a rinse cycle in DI water.
3. Design and architectural problems have greatly reduced cleaning process effectiveness. It is suggested that alternative designs for the MLP FET, which do not contain any hindering flow channels, be assessed. A similar suggestion would be to modify design rules in such a manner so as to provide enough standoff beneath components. This can be seen with the example of the 1210 chip capacitors, which have a copper pad beneath them and are hence, inefficiently cleaned. It is postulated that a better board design

would require ultrasonic cleaning with only DI water for optimal cleaning performance. This would be beneficial, both in terms of performance and cost [2].

7.3 Future Work

The following is the research work which can be carried out in the future in the area of flux residue cleaning:

1. In view of the recommendations given in Section 7.2, it would be imperative to test the effect of the ultrasonic agitation and chemical agent on product performance and reliability. Electrical, mechanical and chemical tests would need to be performed to ascertain that cleaning alternative will have no negative impact on the product.
2. Another project following closely with the previous one would be of process qualification and testing. It would be required to set up and implement the new process in terms of reliability tests and process control tests.
3. Implementation of design rule changes would need to be done in order to maximize cleaning process performance.
4. During the course of the study, it was seen that improper cleaning of the solder flux residue can lead to a lot of problems with regards to solder voiding and solder balling. It would be beneficial to look into these aspects to holistically solve issues related to cleaning.

References

[1] Mukherjee, I., 2011, "Cleaning Process Development and Optimization in the Surface Mount Assembly Line of Power Modules," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

[2] Rajendran, N., 2011, "Surface Mounted PCB Cleaning Process Improvement and its Impact on Manufacturing Systems Performance," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

[3] University of Bolton, http://www.ami.ac.uk/courses/topics/0242_undfl/index.html, accessed August 12, 2011

[4] Hansen, K.S., Jellesen, M.S., Moller, P., Westermann, P.J.S., Ambat, R., 2009, "Effect of Solder Flux Residues on Corrosion of Electronics," *Annual Reliability and Maintainability Symposium, Texas, TX*, pp. 502-508

[5] Lee, N.C., 2002, *Reflow Soldering and Troubleshooting: SMT, BGA, CSP and Flip Chip Technologies*, 1st Edition, Newnes

[6] Chaoyun, L., Sang, L., Cui, Z., Hongchun, Z., Jifan, W., Xin, Z., 2006, "Analysis of SMT Residues after Reflow," *8th International Conference on Electronic Materials and Packaging, Hong Kong*, pp. 1-21

[7] Lee, N.C., 2009, "Lead-Free Flux Technology and Influence on Cleaning", *11th Electronics Packaging Technology Conference, Singapore*

[8] Bivins, B.A., Juan, A.A., Starkweather, B., Lee, N.C., and Negi, S., 2000, "Post-solder Cleaning of Lead-free Solder Paste Residues," *SMTA International Conference, Chicago, IL*

[9] Mearig, J., Goers, B., 1995, "An Overview of Manufacturing BGA Technology," *17th IEEE/CPMT International Electronics Manufacturing Technology Symposium, Austin, TX*, pp. 434-437

[10] Lee, N.C., Bixenman, M., 2002, "Flux Technology for Lead-free Alloys and its Impact on Cleaning," *SEMI Technology Symposium: International Electronics Manufacturing Technology (IEMT) Symposium, San Jose, CA*, pp. 316-322

[11] Ghaffarian, R., Mehta, A., Bonner, J.K., Achong, C., Vogler, O., Phillips, D., Chen, A., Mehrotra, M., Siméus, M., Stegura, S., 2000, "Assembly and Cleaning of CSPs for High, Low, and Ultra Low Volume Applications," *APEX Electronics Assembly Process Conference, Long Beach, CA*

[12] Sinni, A., Palmer, M.A., 1997, "Kinetics of Flux Residue Formation in a Humid Environment," *21st IEEE/CPMT International Manufacturing Technology Symposium, Austin, TX*, pp. 152-156

[13] McDermott, E., Macauley, H., 2008, "Water Wash Process Optimization," Vicor Corporation, Andover, MA

[14] "DOE Study for Identification and Development of PCB Defluxing Process," Technical Report, 2011, Vendor A

[15] Technical Report, 2011, Vendor B

[16] Company Document, Vicor Corporation, Andover, MA