UNIVERSITI PUTRA MALAYSIA

MINIMIZATION OF COPPER DISSOLUTION FOR LEAD-FREE WAVE SOLDERING IN SURFACE MOUNT TECHNOLOGY

MAGESWARAN A/L ARUNASALAM

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By

MAGESWARAN A/L ARUNASALAM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Engineering

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DEDICATION

My path of life started realizing with my beloved father's ambition and determination of helping others to achieve his unachieved goal of life by continuing his studies and completing his doctorate. His unlimited love, trust, guidance and motivation of facing life beyond limits had pushed and motivated me doing thing others say impossible. Due to all his sacrifices for others and me, I would like to dedicate this thesis to my beloved father, Arunasalam Retnam.

My second dedication goes to my mother, Batmawathy Ramaihya and my wife, Suguna Krishnan who had continue supporting the dream of my father during difficult and challenging times, being there for me when everyone had given-up, sacrifices their time for me to continue my father's dream and guiding me to make my own dream out of my father's dream by setting up goals and benchmark of sky are the limits for studies for my beautiful kids, Mohanishwaran, Matheysvaar and Myshaliny.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Engineering

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November 2017

Chairman : Associate Professor Zulkiflle Leman, PhD
Faculty : Engineering

In today's surface mount technology, developments are in progress to move towards green manufacturing by converting all leaded soldering process to lead free soldering process. This move has brought towards safer electronic manufacturing and assembly. The conversion has brought goodness for environment but challenges in manufacturing due to metallurgy and chemistry changes. The problems occurs in almost all area starting from printed circuit board assembly (PCBA) design, surface finishing, chemistry composition, temperature control and process controls. The biggest problem has caused printed circuit board (PCB) assemblies to be scrapped due to copper dissolution problem, a condition caused by longer wetting in molten solder to achieve good barrel fills causing the bottom knee of copper layer to diffuse once in contact with molten solder during the lead free wave soldering process and its rework soldering process which causes the copper layer to lose connectivity between layers. At the time of research, there was no proper method and control over the lead free wave soldering process and its rework soldering process that can maximize the solder barrel fills, minimize the copper dissolution problem and increase the cycles in rework soldering. This brought the overall aim of this research to propose a workable and practical solution to maximize solder barrel fills, minimize copper dissolution and increase the cycles in rework soldering. The work was carried out using Six Sigma methodology through define, measure, analyze, improve and control (DMAIC) approaches. Total of five factors were identified and analyzed namely the PCB finishing and copper layer construction in PCB, component terminal and led finishing, soldering flux usage and solder alloy composition, environment control with the use of Nitrogen tunneling. Resulting from analyzing the factors, a more combined controlled factors contributing to maximizing the solder barrel fills from forty to eighty percent directly improving the yields from fifty to eighty five percent, minimization of copper dissolution defect from fifteen to half percent and increasing the cycles in rework soldering from one to three by reducing the direct

contact time to molten solder with optimize solder alloy composition and process control was formulated. With this improvement, an increase of sixty percentage of boards with lower copper dissolution going through the lead free wave soldering and rework soldering were obtained, another forty percent reduction of board being scrapped were also obtained with boards going through the molten solder up to triple the times.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Kejuruteraan

PENGURANGAN PEMBUBARAN TEMBAGA DARIPADA OMBAK PEMATERIAN TANPA PLUMBUM DALAM TEKNOLOGI PENEMPATAN PERMUKAAN

Oleh

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Dalam teknologi pematerian permukaan kini, perkembangan ke arah pembuatan hijau sedang pesat dengan penukaran proses pematerian bebas plumbum. Langkah ini telah membawa kepada pembuatan dan pemasangan elektronik yang lebih selamat. Penukaran ini membawa kebaikan kepada persekitaran tetapi cabaran dalam proses pembuatan. Cabaran bermula dari reka bentuk papan litar bercetak (PCBA), penamat permukaan, komposisi kimia, kawalan suhu dan kawalan proses. Cabaran terbesar yang telah menyebabkan perhimpunan papan litar bercetak (PCB) dibatalkan adalah masalah pembubaran tembaga disebabkan oleh pematerian lama dalam timah lebur untuk mencapai larutan yang baik. Ini menyebabkan lutut bawah lapisan tembaga meresap sekali apabila bersentuhan dengan timah lebur semasa proses pematerian gelombang bebas plumbum sehingga kehilangan sambungan antara lapisan. Pada masa penyelidikan, tidak ada kaedah dan kawalan yang tepat terhadap proses pematerian gelombang bebas plumbum dan proses pematerian rework yang dapat memaksimumkan laras pateri untuk mengisi, meminimumkan masalah pembubaran tembaga dan meningkatkan kitaran dalam pematerian ulang. Ini membawa matlamat keseluruhan kajian ini untuk mencadangkan penyelesaian praktikal dan untuk memaksimumkan laras pateri untuk mengisi, meminimumkan pembubaran tembaga dan meningkatkan kitaran dalam pematerian semula. Proses ini telah dijalankan dengan menggunakan metodologi Six Sigma iaitu melalui pendekatan mendefinisi, mengukur, menganalisis, memperbaiki dan mengawal (DMAIC). Lima faktor telah dikenalpasti dan dianalisa iaitu pembinaan PCB dan pembinaan lapisan tembaga PCB, terminal komponen, pemakaian fluks pematerian dan komposisi aloi solder, kawalan alam sekitar dengan penggunaan terowong Nitrogen. Hasil daripada penganalisaan tersebut, semua faktor yang dikendalikan lebih banyak menyumbang untuk memaksimumkan laras pateri mengisi iaitu dari empat puluh hingga tujuh puluh peratus, meminimumkan pembubaran tembaga dan dari dua hingga setengah peratus dan meningkatkan kitaran dalam pematerian

ulang dari satu hingga tiga dengan mengurangkan waktu hubungan langsung solder lebur dengan mengoptimumkan komposisi aloi pateri dan kawalan proses. Dengan penambahbaikan ini, peningkatan sebanyak enam puluh peratus papan dengan pembubaran tembaga yang lebih rendah melalui pematerian gelombang bebas dan pematerian semula jadi dapat diperolehi, pengurangan 40 peratus daripada papan yang dibatalkan juga diperoleh dengan papan yang melewati solder lebur sehingga tiga kali ganda.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Engineering. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

SMT	Surface Mount Technology
EMS	Electronic Manufacturing Services
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
OTD	On Time Delivery
FPY	First Pass Yield
DFM	Design for Manufacturability
SPC	Statistical Process Control
PTH	Plated Through Hole
OSP	Organic Substances Preservatives
Imm Sn	Immersion Solder
Imm Ag	Immersion Silver
Imm Au	Immersion Gold
SAC	Tin-Silver-Copper
SN100C	Tin-Copper with additives of Nickel and Germanium
FIB	Focused Infrared Beam
SEM	Scanning Electron Microscope
EDX	Energy Dispersive X-Ray
IMC	Intermetallic Compound
DMAIC	Define Measure Analyze Improve Control
GR&R	Gage Repeatability and Reproducibility
DOE	Design of Experiment
FMEA	Failure Mode Effect and Analysis
OCAP	Out of Control Action Plan
RPN	Risk Priority Number
MSA	Measurement System Analysis
SIPOC	Supplier-Input-Process-Output-Customer

CHAPTER 1

INTRODUCTION

1.1 Research Background

The growing needs of electronic appliances in networking, infrastructure and communication following the technology advancement has brought a lot of benefit and ease of work to human kind. With the advancement comes also few challenges in manufacturing this electronics appliances through surface mount technology (SMT), where for instances the usage of lead in the solder alloy creating easier and reliable joints in electronics manufacturing was used. The character of lead which is easily extracted and refined into assemble joint with lower energy has given advantages in manufacturing electronic appliances but also causing significant problem due it's mammalian toxicity where lead elimination was actively carried out. (Warwick, 2014)

The elimination of lead in assemble replaced with lead free solder alloy had created safer product to human and environment but created bigger challenges in manufacturing electronic appliances especially in SMT from the aspect of;

i. Significant cost increased due to lead free alloy such as silver, bismuth and gold introduced in solder alloy composition
ii. Significant temperature increased with higher melting temperature for the lead free solder alloy
iii. Obviuos grainy and frosty solder joint formation observed
iv. Poor wetting characteristic due to lead free alloy
v. Significant decreased in solder barrel fills for plated through hole (PTH) component
vi. Significant increased in copper dissolution
vii. Significant increase in equipment maintenance due to higher operating temperature.

All this challenges was addressed individually over the years through exstensive studies in solder alloy composition, printed circuit board assemble (PCBA) surface finish, component surface finish, flux chemisty and environmental control over high operating temperature mainly on SMT processes. (Seelig and Suraski, 2009)

With all the studies carried so far in addressing the lead free soldering concentrating on individual aspect of the challenges without combine studies of all the factors due to limitation of resources and application, this research is completed looking into combined factors as process improvement for SMT concentrating in lead free wave soldering process and its rework soldering where the biggest challenges occuring every day concerning electronic manufacturing services

(EMS) industry. This research would give users in EMS a calculated solution addressing to the current issues and future potential issues of lead free wave soldering process and its rework soldering process.

Narrowing down the biggest challenges for lead free wave soldering process and its rework soldering process which is insufficient solder barrel fill for PTH component leading directly to maximizing the copper dissolution and reducing the number of cycles it can go through the molten solder. Extensive copper dissolution causes PCBA to scrap due to the lost of total connectivity between layers.

Resulting from this phenomenann, higher scrap rate totaling to fifty percent with scrap cost amounting more than two hundred fifty thousand dollar are caused by the exstensive copper dissolution, EMS industries are facing huge loses with experiencing low first pass yield (FPY) hovering around forty to fifty percent which are leading to missing their on time delivery (OTD) to end customer. Apart from this, huge investment are needed into the conversion of the lead free wave soldering machines and its rework soldering machines as this machines need different alloy composition and plating in the fluxing, preheating and solder pot compartment.

Maintenance cost to maintain this machines increases rocket high almost triple than the leaded process as erosion are expedite with usage of more aggressive flux and operating in high temperature for the lead free wave soldering process and its rework soldering process. Numerous mechanical and electrical parts like motors, bearings, conveyor chain, flux and wave nozzle, solder pot ducting, impeller, preheater heating element, cable and control cards had to be replace more frequently as wear tear are expedite.

Process control cycle for the solder bath in lead free wave soldering machine and its rework soldering machine whereby purity test cycle is considered has increases from yearly for leaded solder to monthly for lead free solder. Apart from this, investment into process control equipment like the fluxometer to measure and ensure good uniformity, coverage and penentration of flux on PCBA, wave rider to measure the parrellism of conveyor, preheating profile and solder contact length with time between fixed and moveable rails to ensure lead free wave parameter are optimized.

With all the challenges identified, this research has summarize and zoomed into the factors that could and minimize the occurance of copper dissolution by controlling the individual and combition of all the factor contributing. The factors identifiead are;

i. PCB surface finishing considering organic substance preservative (OSP), immersion solder (Imm Sn), immersion silver (Imm Ag) and immersion gold (Imm Au) with direct correlation to surface tension which promotes solder wetting and PCB layer contruction considering high glass transition (Tg) FR4 together with Megtron 6 material which gives the flexiblitiy of pad designing and with standing high operating temperature without disturbing the solder quality.
ii. Component terminal and led surface finishing with respect to the PCB finishing contributes to good solderbility which are achieved through lead free wave soldering and its rework soldering together with solder alloy composition that gives more uniform intermetallic layers minimizing the copper dissolution rate. The component terminal and led surface finishing also determine the oxidation rate which directly effect the solderbility which led to longer contact time in lead free wave soldering and its rework soldering causing high copper dissolution rate.
iii. Flux types and its solid content responsible to clean up the soldering area, and acts an agent to promote soldering. It has activation temperature which would be the requirement for preheating in lead free wave soldering process and would its function into promoting soldering would reduce the contact time in molten solder. Solder alloy composition plays the role of connecting the PCBA to PTH component and directly determine the copper dissolution rate as it has one of the highest influence in melting temperature, solder strength and also intermetallic layers.
iv. Environmental control over lead free wave soldering and its rework soldering are in the area of controlling over oxidation level and heat transfer rate. The option of soldering in nitrogen inert condition either in only solder pot area or the entire lead free wave soldering process from fluxing, preheating and soldering gives the most optimum environmental control needed to maximize heat transfer rate to PCBA to achieve the flux activation temperature and reduce the contact time in molten solder. Apart from this, the nitrogen inert condition will also control the oxidation on PCBA to minimize also the contact time which are one of the factor contributing to high copper dissolution rate.
v. Differences between in-contact soldering and non-contact soldering process directly impact the copper dissolution rate due. The biggest impact are from molten turbulence solder in contact during lead free wave soldering and its rework soldering.This are the main factor in this research compared within the in-contact soldering and its process parameter by optimizing resulting minimum copper dissolution rate in lead free wave soldering and its rework soldering.

1.2 Problem Statement

The biggest challenges in SMT Industries currently, moving forward and in future are lead free wave soldering and its rework processes. This is due to no proper method and controls over lead free wave soldering processes causing insufficient solder barrel fills in PTH component leading to longer soaking in wave soldering and rework soldering causing extensive copper dissolution on PCBA, where the bottom knee of copper layer tends to erode once in contact with molten solder during lead free wave soldering and lead free rework soldering reducing the cycles exposed in molten solder.

Fifty percent of the PTH yield fallout for PCBAs are contributed from insufficient solder barrel fills defect, a condition where solder barrel fill from bottom to top are only forty percent of the PCBA thickness area in lead free wave soldering and rework soldering. Due to low solder barrel fills condition, PCBAs are exposed to longer contact time in molten solder to achieve acceptable barrel fills of more than seventy five percent which are the highest contributor to copper dissolution and scrap rate amouting fifteen percent. This condition has also caused the rework cycle to be only once and in some cases none. The PCBAs are scrapped due to extensive copper dissolution till causing no connection to bottom knee of copper layers as shown in Figure 1.1 which are non-reworkable. With the high percentages of boards been scrapped, it directly increases the scrap cost for EMS industries which was alarming as effecting the whole manufacturing cost which was track in average between the top three EMS industries as shown in Figure 1.2.

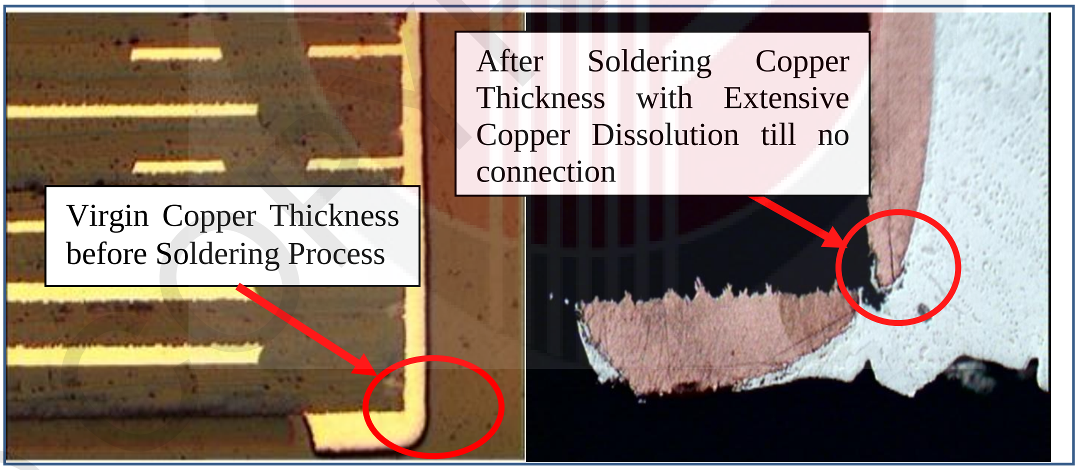

Figure 1.1 : Virgin Copper Layers versus Soldered Copper Layers with Extensive Copper Dissolution

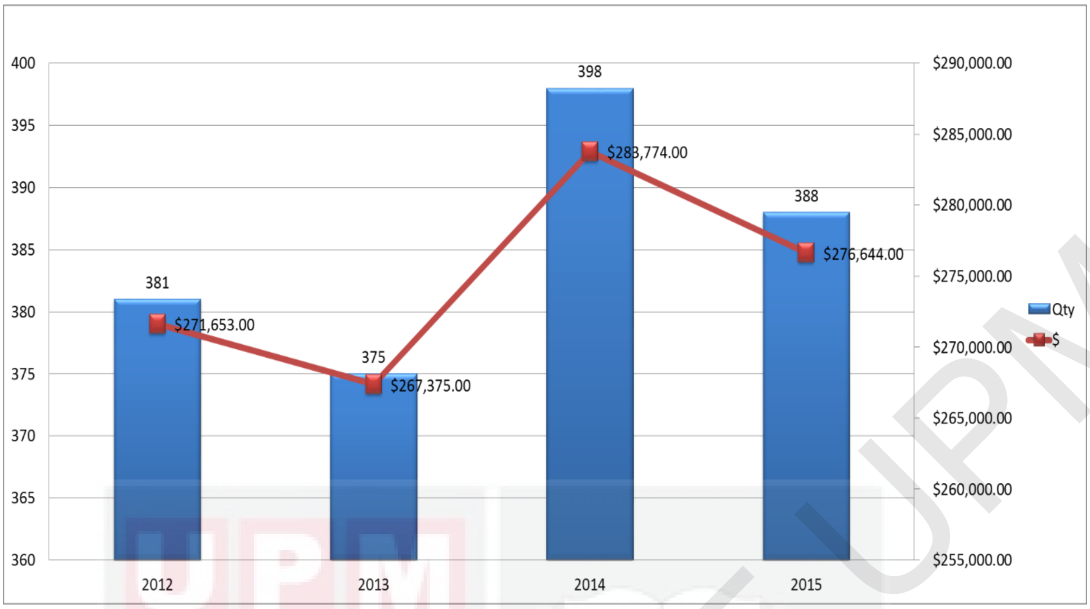

Figure 1.2 : Scrap Quantity and Cost Due to Copper Dissolution Yearly in EMS

Drastic increase of copper dissolution was observed from the year of 2014 as almost all product in SMT has to be converted to lead free which are required as part of worldwide conversion legislation. Copper dissolution minimization activities in lead free wave soldering process are actively been carried individually according to the printed circuit board (PCB) design, thermal analysis, thermal relief design and final PCB layer finishing, component body composition and terminal finishing, soldering bar composition for molten solder in lead free wave soldering and lead free wave soldering flux composition, environment control by running with and without inert nitrogen during soldering or throughout the lead free wave soldering process and by the process itself either through conventional wave soldering, selective soldering, intrusive soldering or robotic soldering.

Without the consideration of the overall combination of variable, copper dissolution minimization are not maximize as the interaction between this variables are not optimize. Apart from this, there are no specific equation quantifies the copper dissolution with the combination of the five variables in lead free wave soldering.

The available equation in minimizing the copper dissolution are within the individual variable details only such the usage SN100C solder bar in molten lead free soldering pot reduces the copper dissolution due to solder alloy composition it carries and stabilization of intermetallic layers. Without the combination of the overall lead free wave soldering variable needed such as what type of PCB finishing, component lead finishing, flux chemistry, soldering environment and process needed, the minimization of copper dissolution are limited.

1.3 Research Objectives

The overall aim of this research is minimization of copper dissolution for lead free wave soldering in surface mount technology. To achieve this aim, specific objectives have been formulated;

1) To propose new process control technique in machine and parameter setting to maximize solder barrel fills in lead free wave soldering.
2) To develop new method in lead free wave soldering and rework soldering to minimize copper dissolution.
3) To increase cycles of mini pot lead free rework soldering.

1.4 Research Scope

Clear direction and variable to achieve the objective with research scope was drawn down from overall lead free wave soldering process and its rework soldering process. The research scope covers the five contribution factor to copper dissolution in lead free wave soldering which includes product, component, chemistry, environment control and process. The copper dissolution occurrence in lead free wave soldering process is zoomed down in detail process combination to root down the area of copper dissolution contributed.

Further detail analysis from individual factors of copper dissolution are been investigated and confirmed as factors contributing to copper dissolution. Within the overall PCB product as the first factor, detail analysis on PCB finishing such as organic substance preservative (OSP), Immersion Silver (Imm Ag), immersion gold (Imm Au) and immersion solder (Imm Sn). (Prasad, 2008). Along with this the PCB Material construction using FR4 which are a glass-reinforced epoxy laminate sheet with high glass transition temperature (Tg) material and megtron 6 which are manufactured with 100% CAF resistant nittobo glass with high frequency circuit board application but with low dielectric constant (Dc) and Dississapation Factor (Df). megtron 6 also has the characteristic of high Tg material due to its laminate construction with blend resin system.

Looking into PTH component details as the second factor, its body composition which are plastic, ceramic, metal and glass plus its terminal and leg finishing which are copper, tin and silver are analyze as part of the lead free wave soldering contributing to copper dissolution. Apart from this, detailing in chemistry specifying into flux usage during lead free wave soldering whereby the solid content and rosin content plus the soldering material composition in alloy formation such SAC305, SAC0307, SAC405 and SN100C with different melting temperature are considered as the third factor. (Hamilton et al., 2007)

Environmental control in lead free wave soldering are analyze by calculating the oxygen level appearance by part per million (PPM) in the soldering environment as the forth factor. With the appearance of high oxygen level in lead free wave soldering, it causes low heat transfer during preheating process and high oxidation during soldering to PCB and Component with copper finishing apart from causing high dross formation and longer contact time to molten solder leading to higher copper dissolution.

This situation are control by creating nitrogen inert environment through tunneling construction either throughout the lead free wave soldering process from the fluxing, preheating and soldering or only in the soldering area to reduce the oxygen ppm level by creating the nitrogen inert curtain layer in lead free wave soldering.

With the inert nitrogen tunneling, the heat transfer to PCB during preheating increases which are curial element in flux solid activation and preparation of PCB for minimal contact time on molten solder during the lead free wave soldering to ensure minimal copper dissolution.

Apart from this four factors above, the fifth factor detail contributing to lead free soldering are the process itself. Minimum copper dissolution are obtained with non-contact lead free soldering method which within the intrusive soldering or reflow soldering with paste in hole technology and Robotic Soldering where soldering are perform within iron tip contact area which are also within the PTH. The wave soldering and selective soldering are conventional molten solder soldering process which has high tendency of copper dissolution.

This research covers only four factor surrounding copper dissolution starting with product where PCB finishing and layer contruction is considered, second on component where component terminal and led finishing is considered, third on chemistry where flux types and solder alloy composition is considered, the last and the forth is environment where environmental control with Nitrogen tunneling during lead free soldering and rework soldering is considered. (Hamilton et al., 2009).

The non-contact soldering was not covered in this research as the resource neither the facilities was complete to perform this research. The four factors in this research covers all the combination available in EMS industries currently and challenges in fifth factor for the non-contact soldering where due to the limited technology available and had stop this research looking into it.

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