EXPERIMENTAL AND SIMULATION STUDY ON LEAD-FREE SOLDERS AND ELECTROLESS NICKEL IMMERSION SILVER SURFACE FINISH

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This project is submitted in
Fulfilment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

JULY 2023

SPECIAL GRATITUDES TO:

MY BELIEVED PARENT,

Norila Binti Mamat

For her supports in whole of my life

MY HONOURED SUPERVISOR

PM Ir. Dr. Saliza Azlina Binti Osman

For her advice and support during the completion of this project

MY RESPECTED CO-SUPERVISOR

PM Ts. Dr. Ervina Efzan Binti Mhd Noor

For her support throughout this project

AND ALL MY COLLEAGUES,

For their encouragement, cooperation and effort in this study

Only Allah S.W.T can repay your kindly

ACKNOWLEDGEMENT

First of all, I would like to express my thanks and Alhamdulillah to Allah S.W.T because of his will and gift, this research is completely done by the given time.

There are no proper words to convey my deep gratitude and respect for my supervisor, PM Ir. Dr. Saliza Azlina Binti Osman for the patient guidance, encouragement monitoring and advice she has provided throughout my time as her student. Special respected to my co-supervisor, PM Ts. Dr. Ervina Efzan Binti Mhd Noor for her support throughout this project.

Special thanks to my beloved parents, Norila Binti Mamat for their trust, timely encouragement and endless patience.

Thousands of thanks to all my fellow friends who help me to finish up my project. Finally, I would like to thank those who have contributed directly or indirectly to the success of this research project.

ABSTRACT

Simulation technology has come a long way in recent years technologies play an important role in revolutionising many industries including electronic industries. Thermal simulation provides deeper insights into a product's behavior with different temperature scenarios, and the designs will be impacted by temperature changes. Knowing these outcomes enables to quickly adjust designs to achieve peak product performance. Therefore, this study aims to investigate the experimental and simulation on lead-free solders with ENIMAG finish. The PCB package's thermal distribution and total deformation were simulated using the ANSYS software. For experimental study, two low melting point of lead-free solders was used which are Sn-40Bi, Sn-4.0Zn-40Bi and Sn-3.0Ag-0.5Cu as comparison. ENIMAG/Cu was used as a substrate and was reflowed at 150°C for both Sn-40Bi and Sn-4.0Zn-40Bi lead-free solders. Then the substrate undergone isothermal aging process at 55°C for Sn-40Bi and Sn-4.0Zn-40Bi and different aging durations (250, 500, and 750 hours). The top surface and cross-sectional examination were characterised using optical microscope and scanning electron microscopy (SEM). The results revealed that both thermal distribution in steady-state and transient thermal shows temperature over the PCB surface is equilibrium and even for both reflow temperatures during reflow soldering and aging process. The temperature of the PCB becomes close to the ambient temperature at the end of the given time and high at the middle of PCB. For aging process, there was no or small deviation was observed for all parameters. The lowest temperature is recorded on the edge of the PCB in some cases, but the deviation is minor at 0.001°C. For aging process, maximum stress on the PCB is 195.59 MPa and minimum stress is 5.9326 MPa for 150°C while for 250°C is 753.51 MPa and 22.856 MPa for maximum and minimum stress, respectively. Besides, in the as-reflow condition, the IMC thickness for Sn-40Bi is thinner than Sn-4.0Zn-40Bi and SAC305 solder. Duplex IMC of $(Cu,Ni)_6Sn_5$ and $(Ni,Cu)_3Sn_4$ was detected at the interface of solder joint for all solder materials. During isothermal aging process, the IMC thickness for Sn-40Bi is maintain thinner than Sn-4.0Zn-40Bi and SAC305 solder. However, The IMC thickness is increased when the aging duration is increased for all solder materials. Moreover, the grain sizes of IMC morphology are changing to become rounder and denser when it was exposed to aging process.

ABSTRAK

Teknologi simulasi telah berkembang dengan pesat sejak beberapa tahun kebelakangan ini, teknologi memainkan peranan penting dalam merevolusikan banyak industri termasuk industri elektronik. Simulasi terma memberikan wawasan yang lebih mendalam mengenai tingkah laku produk dengan senario suhu yang berbeza, dan reka bentuk akan dipengaruhi oleh perubahan suhu. Mengetahui hasil ini membolehkan untuk menyesuaikan reka bentuk dengan cepat untuk mencapai prestasi produk puncak. Oleh itu, kajian ini bertujuan untuk mengkaji eksperimen dan simulasi pada pemateri tanpa plumbum dengan kemasan ENIMAG. Pengagihan terma pakej PCB dan jumlah ubah bentuk telah disimulasikan menggunakan perisian ANSYS. Untuk kajian eksperimen, dua takat lebur rendah pemateri bebas plumbum digunakan iaitu Sn-40Bi, Sn-4.0Zn-40Bi dan Sn-3.0Ag-0.5Cu sebagai perbandingan. ENIMAG/Cu digunakan sebagai substrat dan dialirkan semula pada 150°C untuk kedua-dua pemateri bebas plumbum Sn-40Bi dan Sn-4.0Zn-40Bi. Kemudian substrat mengalami proses penuaan isoterma pada 55°C untuk Sn-40Bi dan Sn-4.0Zn-40Bi dan tempoh penuaan yang berbeza (250, 500, dan 750 jam). Pemeriksaan permukaan atas dan keratan rentas dicirikan menggunakan mikroskop optik dan mikroskop elektron pengimbasan (SEM). Keputusan menunjukkan bahawa kedua-dua taburan haba dalam keadaan mantap dan terma sementara menunjukkan suhu di atas permukaan PCB adalah keseimbangan dan juga untuk kedua-dua suhu aliran semula semasa pematerian aliran semula dan proses penuaan. Suhu PCB menjadi hampir dengan suhu ambien pada penghujung masa tertentu dan tinggi di tengah PCB. Untuk proses penuaan, tidak ada atau sisihan kecil diperhatikan untuk semua parameter. Suhu terendah direkodkan pada tepi PCB dalam beberapa kes, tetapi sisihan adalah kecil pada 0.001°C. Untuk proses penuaan, tegasan maksimum pada PCB ialah 195.59 MPa dan tegasan minimum ialah 5.9326 MPa untuk 150°C manakala bagi 250°C ialah 753.51 MPa dan 22.856 MPa untuk tegasan maksimum dan minimum. Selain itu, dalam keadaan as-reflow, ketebalan IMC untuk Sn-40Bi adalah lebih nipis daripada pateri Sn-4.0Zn-40Bi dan SAC305. IMC dupleks (Cu,Ni)6Sn5 dan (Ni,Cu)3Sn4 telah dikesan pada antara muka sambungan pateri untuk semua bahan pateri. Semasa proses penuaan isoterma, ketebalan IMC untuk Sn-40Bi dipantau lebih nipis daripada pateri Sn-4.0Zn-40Bi dan SAC305. Walau bagaimanapun, ketebalan IMC meningkat apabila tempoh penuaan ditingkatkan untuk semua bahan pateri. Selain itu, saiz bijian morfologi IMC berubah menjadi lebih bulat dan padat apabila ia terdedah kepada proses penuaan.

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LIST OF SYMBOLS AND ABBREVIATION

Ø	Diameter
ºC	Degree Celcius
ENImAg	Electroless Nickel Immersion Silver
CTE	coefficient of thermal expansion
IMC	Intermetallic Compound
ENIG	Electroless Nickel/Immersion Gold
PCB	Printed Circuit Board
RoHS	Restriction of Hazardous Substance
JEDEC	Joint Electron Device Engineering Council
OM	Optical Microscope
SEM	Scanning Electron Microscopy
CTE	coefficients of thermal expansion
HASL	Hot Air Solder Levelling
CFD	Computational Fluid Dynamics
OSP	Organic Solderability Preservative
IPC	Association Connecting Electronics Industry
ImSn	Immersion Tin
ENEPIG	Electroless Nickel Electroless Palladium Immersion Gold

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CHAPTER 1

INTRODUCTION

1.1 Background Study

There is an ongoing miniaturisation around microelectronics driven by an increasing requirement for mobility and more complex functionalities such as in the automotive or portable industry. The minimal feature size within semiconductors continuously decreases, whereas the number of transistors rapidly grows. Consequently, the demands on strength and lifetime of the used materials considerably rise while the material size continuously reduces (Thomas & Wolfgang, 2008). In semiconductor devices, the solder joints between the die and the substrate and the substrate and base plate are subjected to thermal and mechanical stresses during the processing and subsequent operation. The solder die attach is regarded as a critical site in high-temperature power modules. The existence of temperature gradients during the service and mismatch of the coefficient of thermal expansion (CTE) of the neighbouring materials results in thermos-mechanically induced stresses in the soldered layers of the devices (Yilun Xu *et al.*, 2022; Samia, Abdel Moghny & Syed Ismail Ahmad, 2022; Khatibi, Betzwar & Lederer, 2018; Lutz *et al*., 2011). Intermetallic compound (IMC) is formed when a metallurgical reaction occurs between the molten solder and the copper board during the reflow soldering process. Thickness and particle volume fraction are important criteria for thermal and electrical conductivity of solder joints. The thinner the IMC layer, the better the interface bonding (Montajar *et al.*, 2022). The formation of a thin layer of IMC between solder and conductive metals is necessary for metallurgical bonding but the reliability of the solder joint is reduced when these IMCs become too thick due to their ability towards structural defects because of its brittle nature (Ismail *et al.*, 2022; Muhammad Aamir *et al*., 2017). Solder joints in electronic devices are a key component of the assemblies whose reliability concern increases at elevated temperatures of operations due to the growth of intermetallic compound (IMC) in the joints and the accelerated degradation of the solder alloys (Amalu & Ekere, 2012). Another important aspect of solder joint processing is a good understanding of the solder-substrate metallisation reaction. The intermetallic layer, which develops from this reaction, is essential to achieve strong and reliable solder joints. However, excessive growth of intermetallic layer may lead to degradation of solder joint reliability (Ismail *et al.*, 2022; Chang *et al*., 2007). Thus, to improve the understanding of the material response, finite element analysis needs to be considered. Since the mechanical reliability of solder joints is, to a large extent, governed by possible embrittlement of the material, one needs to investigate the strain to fracture observed in the aged solder alloys. In this context, simulation modelling provides helpful information about the stress and strain distribution in the material. Due to a constraint effect, the strain in the solder joint is not distributed homogeneously. Instead, there are high-stress concentrations at the periphery along the edges (Khatibi, Betzwar & Lederer, 2018; Lederer, Khatibi & Weiss, 2012). Besides that, simulation modelling can also analyse the state of thermal and mechanical stresses and strains in the samples during the reliability test (Khatibi, Betzwar & Lederer, 2018). Substrate metallisation is very important, especially in the microelectronic area. The interaction between substrate metallisation (surface finish) can affect the solder joint properties. Thus, the move towards lead-free soldering has resulted in the surface finish requirements to become an even more important aspect in today's printed circuit fabrication. Although several alternative surface finishes have been developed over the years, electroless nickel/immersion gold (ENIG) surface finish has maintained a popular choice in electronic packaging as it provides a uniformly flat surface finish, which is an excellent solder attachment process control and high performance (Yoon & Jung, 2008; Biunno, Barbetta & Clara, 2006). However, with significant volatility in precious metal pricing and the constant demand for better products at cheaper prices, manufacturers are encouraged to search for ways to reduce cost whilst not sacrificing quality (Wang, Tsai & Lai, 2012; Long & Toscano, 2013).

1.2 Problem Statement

Reflow soldering technique has been widely used in the electronic industry. This soldering process is very cost effective and efficient in the soldering of PCB package. However, a common problem is encountered during the reflow soldering and the isothermal ageing process, which is burnt PCB or overheated solder joint on the printed circuit board due to uneven thermal . The mechanical behaviour, strength, and quality of solder joints will be affected, and those failures will influence the performance and sustainability of the printed circuit board. The completion of reflow soldering always has a common issue, which is lifted components. Lifted components on PCBs can occur due to a mixture of physical and thermal problems. The heat produced during the soldering process can lower copper adhesion, causing the PCB to become very weak and will eventually cause failure in a short time.

In addition, the Restriction of Hazardous Substance (RoHS) has banned the use of tin-lead (Sn-Pb) and changed it to lead-free solder because of human health and environmental problems. Lead usage is dangerous because when it enters the human body through inhalation and feeding contact. Several lead-free solder alloys appear to have the potential to replace lead-containing solders to fulfil the legislation.

Currently, many surface finishes are applied on printed circuit board (PCB) in the electronics industry. Electroless Nickel/Immersion Gold (ENIG) finish is a surface finish that offers great characteristics and ideal for printed circuit board (PCB) and makes ENIG very popular. However, the ENIG surface finish has weakness due to gold metal and black pad issues. ENIG is a very expensive surface finish due to the costly gold price. If an alternative surface finish can replace ENIG, it has the potential to offer better properties and lower cost than ENIG and this will help to define the sustainability of the package.

1.3 Objectives

This project embarks on the following objectives while achieving the aim of this research:

i. To simulate the effect of reflow soldering and isothermal aging temperature on printed circuit board (PCB) by using modelling software.
ii. To examine the effect of lead-free solders and Electroless Nickel/ Immersion Silver (ENIMAG) surface finish during the soldering process
iii. To evaluate the isothermal aging process on interfacial reactions in terms of intermetallic compound (IMC) thickness, type and morphology,

1.4 Scope of Study

The scopes of this project are as follows:

i. Simulation process by using CFD-ANSYS software version 2020.
ii. Deposition of ENIMAG surface finish on copper substrates using electroless and immersion plating process,
iii. The use of low temperature lead-free solders: (1) Sn-40Bi, (2) Sn-4.0Zn-40Bi, and (3) Sn-3.0Ag-0.5Cu (SAC305) as reference.
iv. Reflow soldering at 150°C for both Sn-40Bi and Sn-4.0Zn-40Bi lead-free solders.
v. Conduct low temperature isothermal ageing at 55°C for Sn-40Bi and Sn-4.0Zn-40Bi and different ageing duration (250, 500, and 750 hours) by following a storage test in JEDEC standard (JESD22-A119A).
vi. Characterisation of IMC during reflow and isothermal ageing using OM, SEM, EDX, and XRD.

1.5 Significance of study

The study of thermal distribution on the surface of PCB package is very important. This test will help to notice whether the heat generated by the whole process is uniformly distributed on the whole surface of PCB package and the quality completed in the soldering process is guaranteed. This is because if the heat is uneven or not uniformly distributed throughout the process, then the solder joints that receive more heat will affect the mechanical properties and not able to be long-lasting. Besides that, it is important to avoid the concentration of hot spots on the printed circuit board, distribute the power evenly on the printed circuit board as much as possible, and keep the PCB surface temperature performance uniform and consistent. Not only for the circuit board, the importance of this research also lies in the fact that when the solder joint is subjected to the process of reflow soldering, isothermal ageing process at long ageing time and high ageing temperatures, the mechanical behaviour and quality of the solder joint have a great impact on printed circuit board package.

Furthermore, this study can provide the fundamental knowledge including the capability needed in the reflow soldering process to know the solder joint reliability. The use of ENImAg surface finish and Sn-Bi solder material will help to slow down the intermetallic formation and growth during the solder-board surface finish interaction. The slow reaction of intermetallic growth will reduce the intermetallic thickness and avoid intermetallic embrittlement. Thus, it will hopefully stay stable at low temperature and high during isothermal ageing process and would provide higher lead-free solder joint reliability. Besides that, the investigation can also provide a good understanding regarding the effects of low temperature during isothermal ageing process on the IMC formation and growth.

1.6 Thesis Outlines

This thesis contains five chapters where each chapter addresses different objectives. Each basic chapter addresses several topics and is divided into subchapters. The first chapter is an introduction, the overview of the problem statement including the objectives and scope of study. Chapter two shows the context literature review regarding this research. A detailed methodology is described in chapter three. Meanwhile, chapter four presents the findings and results obtained. Finally, the conclusion and recommendation are elaborated on the significance of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Soldering Technology

Soldering is a generally longstanding innovation. Different subjects on soldering innovation have produced a lot of intrigues, especially in the hardware gathering industry. Present-day soldering technology improvement includes solder organisations just as joining forms upgrades. In any case, any progressions in soldering innovation must be receptive to new guidelines and as per present enactment, for the most part, because of concerns regarding wellbeing and the earth. Every key perspective related to soldering innovation will be talked about in detail in this section.

2.2 Solder Constitutive Model

Solder is a fundamental material used in the assembly of electronic devices to printed circuit boards (PCBs). There are three important functions of the solder interconnections: mechanical support, electrical connection, and thermal dissipation. During the service of electronic devices, the package/PCB assembly is subject to changes in temperature owing to cyclical power on/off status and computational activity. In such temperature variations, thermally induced stresses arising from the dissimilar coefficients of thermal expansion (CTE) of packaging materials could cause the solder joints to fail, and eventually compromise the functionality of the whole packaging assembly. Along the progress of science and technology, the ever-increasing demands of high performance, multi-function, and miniaturisation for electronic devices have introduced a considerable challenge in the reliability design of solder joints (Gang, Xiaochen & Wu, 2017). Besides that, the mechanical behaviour of solder depends on the joint microstructure and is affected by many parameters such as intermetallic, joint or specimen size, cooling rate of the assembly after soldering, and ageing in service. Thus, constitutive models have been developed to help characterise the mechanical behaviour of solders. Various constitutive models are available throughout the literature for lead-free solders (Liang, Zhi-quan & Yu-ong, 2016; Gang, Xiaochen & Wu, 2017; Che *et al*., 2006). The material constitutive model plays the most important role in the development of electronic reliability design because the stress, strain, and strain energy density adopted in finite element modelling and fatigue-life prediction are all computed and derived from the constitutive model. Solder joints are the most widely used interconnection materials in electronic product packaging. The failure of the whole electronic packaging is often induced by the failure of solders, hence, modelling and simulation of solder joint performance are quite important in ensuring the quality and reliability of electronic products. In fact, the accuracy of reliability design of electronic packaging depends on accelerated reliability tests, material constitutive models, finite element modelling, and fatigue-life prediction models (Gang, Xiaochen & Wu, 2017).

2.3 Surface Finish Metallurgy

Surface finish can be defined as a layer, whether metal or organic in nature, which are used in a printed circuit board to ensure the solder metal capacity under a plate after going through various storage times and conditions. During the soldering process, the type of surface finish will influence the type of IMC formed. It is necessary to form a thin IMC layer to ensure that the interface is bonded while any excessive IMC formation enhances embrittling of the solder joint. However, IMCs would continually grow under reliability testing and field-use condition. Therefore, metallurgical and mechanical properties are strongly dependent on the surface finish, substrate, and solder. The selection of these materials plays an important role in the reliability of the solder joints (Tong, Chung-Hung & Yi-Shao, 2012). According to Zhang *et al*. (2020), Milad (2008), and Arra *et al*., (2004), several surface finishes have been developed. They can be used in the electronic industry, such as Hot Air Solder Levelling (HASL), Electroless-Nickel Immersion Cold (ENIG), Immersion Silver (ImAg), Immersion Tin (ImSn), Organic Solder Preservative (OSP), and Electroless Nickel Palladium Immersion Gold (ENEPIG). Most of these surface finishes are environmentally friendly and suitable for lead-free solders.

2.3.1 Hot Air Soldering Levelling

Hot Air Solder Levelling (HASL) is the predominant surface finish in the industry. The process consists of immersing circuit boards in a molten tin/lead alloy pot and removing the excess solder using air knives, which blow hot air across the board's surface. Lead-free HASL finish continues to gain momentum as a variable surface finish option. In addition, HASL technology occupies an important position in the PCB industry due to its low cost (Kang *et al*., 2015; Ballarini *et al.*, 2015).

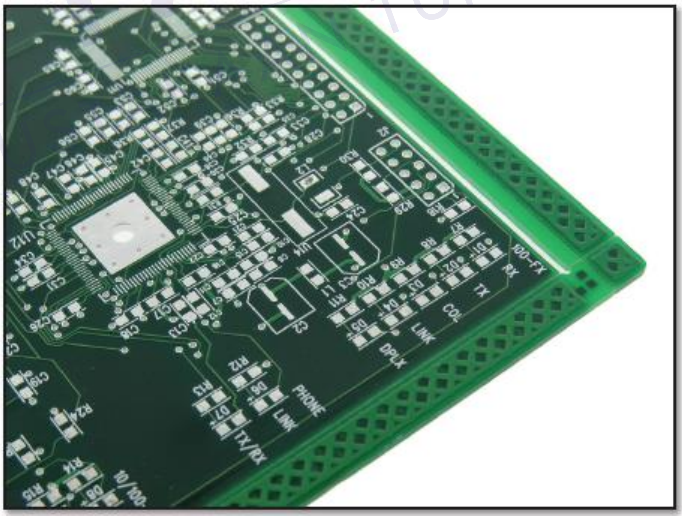

Figure 2.1: Printed circuit board with HASL Surface Finish

Some advantages of HASL are low-period solder wetting, excellent shelf life, great mechanical durability, long storage life, and the formation of intermetallic compound before the printed circuit board (PCB) assembly process (Ballarini *et al.*, 2015; Goodell, 1997). However, an unintended benefit of the HASL process is that it will expose the PCB to temperatures up to 265°C, identifying potential delamination issues before any expensive components are attached to the board. The primary function of HASL is to prevent the surface of PCB from oxidation, impurity, and perfect wetting throughout the process of joining or soldering components. HASL is also helpful for putting solder to the copper surfaces after the solder mask. Bypassing the boards through a hot, molten wave of solder and blasting the excess solder from the boards using a high velocity of hot air, a tiny layer of eutectic solder is plated onto the exposed copper (Nable, 2015). However, poor-quality HASL finishes on PCBs during reflow soldering can cause severe solderability problems. The intermetallic compound (IMC) of exposed copper-tin oxidises and becomes very difficult to wet during reflow (Bin & Yudong, 2013). During the initial stage of this conversion, there were doubts that PCB materials could withstand higher temperatures (Wayne & Sweatman, 2012). Then, the PCB will be broken down and unable to be used anymore, as shown in Figure 2.2 (Yao *et al.*, 2013).

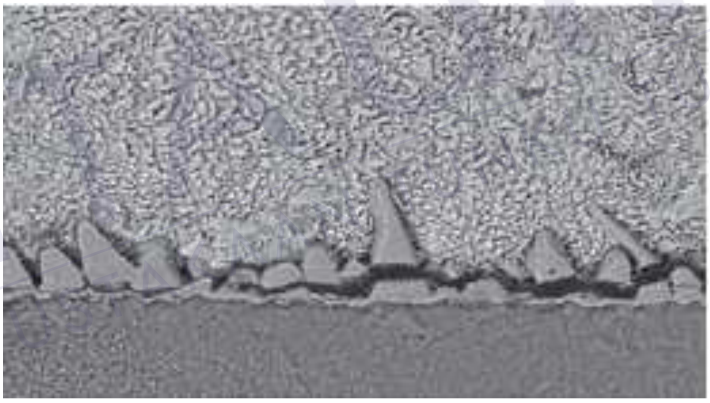

Figure 2.2: HASL Solder Joint Crack on IMC Layer (Yao *et al*., 2013)

2.3.2 Immersion Tin

According to the Association Connecting Electronics Industry (IPC), immersion tin (ImSn) is a metallic finish deposited by a chemical displacement reaction that is applied directly over the basis metal of the circuit board which is copper. Since tin is the main component of lead-free solder, the metallurgical process of ImSn coating is very suitable for lead-free applications. Immersion tin is suitable for small pitch product applications and produces a uniformly flat surface that can be soldered well. (Wang *et al*., 2009). The ImSn protects the underlying copper from oxidation over its intended shelf life. In addition, the chemical tin coating produced by an immersion process provides copper water tubes with cathodic corrosion protection. It is a barrier between the base metal and its environment (Huttunen *et al.*, 2002).

However, copper and tin have a strong affinity for one another. Therefore, the diffusion of one metal into the other will occur inevitably, directly impacting the shelf life of the deposit and the performance of the finish. Schueller (2005) considers this as a good surface treatment for printed circuit boards, as the cost is relatively low and it is a flat surface treatment. The colour of the tin coating is typically white, so the finish is often referred to as White Tin and applied using an electroless chemical bath to the copper. The process of ImSn is relatively easy than other surface finishes (Chen *et al*., 2007).

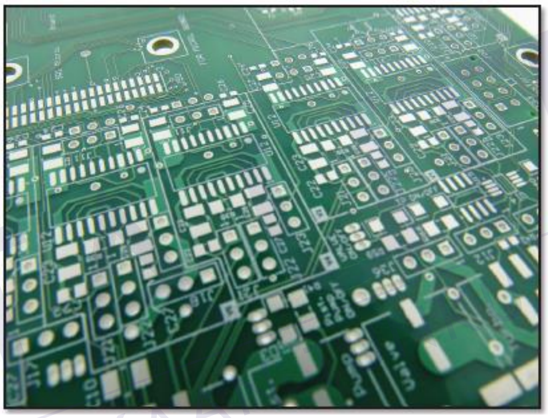

Figure 2.3: Printed circuit board with immersion tin surface finish

2.3.2 Organic Solderability Preservatives

Organic Solderability Preservative (OSP) or anti-tarnish preserves the copper surface from oxidation by applying a very thin protective layer of material over the exposed copper by usually using a conveyorised system to add a very thin protective layer of material over the exposed copper. It uses an organic water-based compound that selectively binds to copper and provides an organometallic coating that protects the copper before soldering. OSP has been used as a PCB surface finish for several years. The benefit of OSP surface finish is it is low cost, goes through a simple process, and has a good integrity of the solder mask (Liu *et al*., 2007).

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