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Solder wicking in surface mount vapor phase reflow soldering

Mulugeta Abtew
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SOLDER WICKING IN SURFACE MOUNT VAPOR PHASE REFLOW SOLDERING

A Thesis
Presented to
The Faculty of the Department of General Engineering
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Mulugeta Abtew
December, 1993

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ABSTRACT

SOLDER WICKING IN SURFACE MOUNT VAPOR PHASE REFLOW SOLDERING

by

Mulugeta Abteu

A full factorial design experiment was carried out to investigate the cause of solder wicking defects in vapor phase reflow soldering of Pin Grid Arrays. The effects of five soldering parameters (flux amount, lead surface roughness, pre-heat time, pre-heat temperature, and reflow time) were evaluated based on the criteria for reliable solder joint formation. The optimum soldering parameter settings found to virtually eliminate solder wicking defects, while minimizing dewetting effects, were average lead surface roughness of 60 μ m, pre-heat time of 480 seconds, pre-heat temperature of 402.1°C, reflow time of 210 seconds, and flux amount of 2 mm³ per component. Reflow time and flux amount showed the most significant effects and the settings for these parameters were much more narrow and critical. The full factorial design proved to be extremely useful in the optimization of the multivariable reflow soldering operation.

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LIST OF ABBREVIATIONS

SMP	Small Micro Package
PGA	Pin Grid Array
MLA	Multilayer Assembly
MLB	Multilayer Board; same as MLA
VPS	Vapor Phase
VPR	Vapor Phase Reflow
BGA	Bump or Ball Grid Array
IP	Inter Poser
ANOVA	Analysis of Variance
DOE	Design of Experiments
MCM	Multi Chip Module
PLCC	Plastic Leaded Chip Carriers
SMC	Surface Mount Component
SMT	Surface Mount Technology
RMA	Rosin Mildly Activated

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CHAPTER 1

INTRODUCTION

Solder wicking is a solder joint defect that occurs when solder rises, or wicks, up the vertical portion of a lead on a leaded component. This results in an open or poor fillet formation at the substrate and component lead joint, which can result in both short or long term mechanical and electrical failures. Solder wicking during vapor phase reflow of Small Micro Package Pin Grid Arrays mounted on a Multi Layered Assembly or Printed Circuit Board is a significant and costly solder joint defect.⁽¹⁾ This thesis describes the physics of solder bond formation in general, and the mechanism of solder wicking in particular, including the detailed analysis and results of a designed experiment that was conducted to determine the cause of solder wicking in the chip-to-board assembly process.

The Small Micro Package (SMP) consists of a chip in a hermetic Pin Grid Array (PGA) package, with 462 pins. Hermeticity is accomplished with Kovar (53% iron, 29% nickel and 17% cobalt) connections to gold-tin solder at the package base, and lead-tin solder at the heat spreader. The gold covered heat spreader interfaces with the cooling bellows of the cooling module during Multi Chip Module (MCM) assembly. Thermal grease is used at this interface. The SMP leads are nickel micro-pins with gold plating. These leads are nickel brazed to tungsten vias that continue to the die connection. The MCM assembly is accomplished by mounting, aligning and vapor phase reflow soldering of the SMP leads on a Bump Grid Array (BGA), called an Inter Poser (IP), mounted and soldered on a Printed Circuit Board (PCB), as shown in Figure 1.

Figure 1. Illustration of SMP mounting on a PCB.

The high lead count of the SMP, coupled with the small pad size of the solder bump on the substrate upon which each SMP lead is mounted, makes it challenging to develop a reflow process that will yield a reliable solder joint that can meet the increasingly stringent mechanical and electrical quality requirements. In addition, the inability to visually inspect almost 70% of the solder joints after reflow makes it extremely important to develop a reflow process with zero solder wicking defects.

One element of electronic packaging that influences the overall packaging strategy is the structure and the joining process used to interconnect packaged electronic devices to higher level assemblies such as boards, cards or substrates. Because of its unique ability to join together materials of varying coefficients of thermal expansion, levels of rigidity, and strength, soldering has been the primary joining technique in component to board assembly of electronics products. Depending on the assembly process and the packaging structure to

be joined, the joining of components and board can be performed in a variety of soldering processes such as Wave Soldering, Infrared Reflow, Laser Reflow, Vapor Phase Reflow, etc.

Vapor Phase Reflow soldering is used mainly in Surface Mount Technology. However, it is still an emerging technology and a fairly complicated process. As a result, it is affected by various problems that can reduce both assembly yield and reliability. One of the most significant problems is solder joint defect. This is frequently encountered in the form of an open joint due to *solder wicking*. "Open joint" is a term used to describe a gap that occurs between a component lead and a board or substrate pad after reflow. Solder joint defects of vapor phase reflowed surface mounted components, due to solder wicking, are not unique. Various electronics industries have encountered this problem and each has devised different methods to eliminate this defect.⁽²⁾ To give the reader a good understanding of the magnitude and scope of solder wicking defects, a review of how the problem manifested itself and how it was resolved at various electronics industries is discussed in Chapter 2. Chapter 3 of this report is a discussion of the theory of solder bond formation and the physics of soldering. In Chapter 4 soldering in surface mount technology in general, and vapor phase reflow soldering in particular, is described. Various soldering techniques, including the heat transfer mechanism in Vapor Phase Reflow soldering, are also discussed. The Design of Experiments conducted to resolve the solder wicking problem is described in Chapter 5. The analysis demonstrates the importance of detailed theoretical study, before the actual design of an experiment, to isolate, identify and validate the few critical parameters of a given process to conduct efficient and cost effective experimentation. Chapter 6 is the discussion of the validity of the methodology used to resolve the solder wicking problem. The conclusions arrived at are presented in Chapter 7. The references utilized in this investigation are listed in Chapter 8.

CHAPTER 2

SOLDER WICKING - A REVIEW

Texas Instruments (TI),⁽²⁾ IBM,⁽³⁾ 3M-Industrial Chemical Products Division,⁽⁴⁾ and Fujitsu⁽⁵⁾ are some of the industries that had experienced solder wicking problems in their manufacturing process. TI, IBM and 3M had encountered solder wicking on Plastic Leaded Chip Carriers (PLCCs), resulting in the formation of open solder joints. Fujitsu had solder wicking problems during vapor phase reflow soldering of SMPs.

In this chapter a detailed description of the solder wicking failure mode encountered and the solutions devised by each of the above companies is discussed. The review contained in this chapter is based upon information available in the open literature. The defects encountered and the solutions developed are summarized in Table 1. It is highly probable that this problem has manifested itself more frequently in most electronics assembly processes, but has not been reported publicly.

2.1. Texas Instruments

The formation of open solder joints due to solder wicking during vapor phase reflow soldering of PLCCs to multilayer PWB was a major solder joint defect.⁽²⁾ To identify the root cause of this defect a detailed investigation and analysis was conducted by Cobb and Spitz.⁽⁶⁾ The investigation identified the temperature difference between the PWB and the component lead and PCB pad metallization as root causes for open solder joint defects.

Table 1. Summary of solder wicking defect causes and solutions identified by various electronics companies.

COMPANY	IDENTIFIED CAUSES	PROVIDED SOLUTIONS
TI	<ol style="list-style-type: none"> 1. Temperature difference between the component lead and the land during VPS reflow soldering. 2. PWB metallization 	<ol style="list-style-type: none"> a. Formulate solder paste that has a delayed reflow effect. b. Accurate prediction of thickness and composition of solder on the land to compensate loss due to intermetallic formation.
3M	<ol style="list-style-type: none"> 1. Temperature difference between the component lead and the land during VPS reflow soldering. 	<ol style="list-style-type: none"> a. Formulate solder paste that has a delayed reflow effect by adding 2% Ag to SnPb eutectic solder.
IBM	<ol style="list-style-type: none"> 1. Oxidation of pad surface 2. Pad surface solderability 3. Heat transfer rate differential between lead and pad 4. Component lead surface finish 	<ol style="list-style-type: none"> a. CuNi plating on lead surface to delay reflow b. Application of epoxy or solder mask to the component lead to serve as solder dam.
FUJITSU	<ol style="list-style-type: none"> 1. Temperature difference between the component lead and the land during VPS reflow soldering. 	<ol style="list-style-type: none"> a. Remove activator from flux to reduce flux wetting action b. Reduce flux amount and prebake assembly before reflow
OTHERS	<ol style="list-style-type: none"> 1. Temperature difference between the component lead and the land during VPS reflow soldering. 	<ol style="list-style-type: none"> a. Create a groove on the component lead perpendicular to the direction of solder spreading. b. Changing orientation of PWB during VPS reflow.

2.1.1. Temperature Gradient

Vapor phase heat transfer to the surface of a material is constant regardless of its composition or geometry. Therefore, the rate of heating is dependent on the mass and

thermal conductivity of the material being heated. Generally, metal leads have low mass and high thermal conductivity relative to the substrate and the land (pad). This difference in mass results in the leads reaching the reflow temperature slightly faster than the land. The solder in contact with the lead will melt first, temporarily drawing the molten solder on the pad surface away from the pad. Failure of the solder to return to and wet the pad will result in an open or starved joint.

To reduce the temperature difference between the lead and the land during VPR, and to ensure simultaneous wetting of the leads and the land, TI formulated a solder paste that has a delayed reflow effect. This delayed reflow effect was produced by mixing pure tin particles with 10/90 alloy (10% Sn, 90% Pb) particles in quantities which yielded a 63/37 solder alloy after reflow.

What TI did was to take advantage of the alloying properties of tin and lead. A 63/37 eutectic solder melts at 183°C. Pure tin, on the other hand, melts at 231°C, which is well above the vapor phase condensation temperature of 215°C. Therefore, if a solder paste is made of either a 10/90 alloy or pure tin, it would not reflow during vapor phase reflow at 183°C. If, however, a paste is made of the exact amounts of pure tin and 10/90 particles to create a net composition of 63/37, reflow will occur. This is possible because solid state diffusion will lead to the formation of a fusible alloy at the interface of the different solder particles. In this manner, all of the particles will eventually melt.

In addition, the delay time of reflow is controlled by the rate of diffusion, which in turn is controlled by the size of the particles making up the paste. Also the extent of reflow delay is affected by prebaking the assemblies prior to reflow. This effect results from an agitation of the solder particles, since large volumes of vaporized solvents are out gassed

during the heating. Agitation causes motion between the particles and speeds up the diffusion process. Prebaking effectively removes the majority of the solvents before reflow and therefore increases the reflow delay.

2.1.2. PWB Pad Metallization

Various methods were used to analyze the solder composition of PWB pads that had high and low solder wicking defects. Results indicated that the tin/lead ratio was 62/38 for the high defect pads and 70/30 for the low defect pads. Even though the solder composition at the high defect pads was closer to eutectic solder than at the low defect pads, when the plated solder on the board was fused, a reaction took place between the tin in the solder and the copper substrate, forming the Cu_6Sn_5 intermetallic compound. This reaction depleted some of the tin from the bulk pad solder. So, if a eutectic tin-lead ratio is plated, a free solder (i.e., that solder on top of the intermetallic after fusing) composition higher in lead than eutectic will result. The free solder composition is important because it is this solder that participates in forming a connection between the component lead and the PWB pad.

When the compositions of the free solder were calculated, for both low defect and high defect PWB pads, the free solder on the high defect board had a tin-lead ratio of 56/44 and a corresponding liquidus temperature of 200°C . The free solder on the low defect PWB pads had a calculated tin-lead ratio of 63/37 and a corresponding liquidus temperature of 183°C (eutectic). Although both solder compositions would most likely melt at VPR soldering temperatures, the solder with the lead-tin ratio of 56/44 would melt more slowly, thereby increasing the temperature difference between the lead and the pad, during reflow.

In the case of electroplated coatings, both plating thickness and composition impact the composition of the free solder after fusing. Both parameters need to be accurately predicted to achieve the optimum near eutectic composition of the free solder. Once the variation in solder composition was identified as a root cause for wicking, parameters that control PWB electroplating composition, namely the current density variations in the plating path, were identified and optimized.

2.2. 3M- Industrial Chemical Products Division

Frequent solder wicking problems were encountered during VPR of surface mounted leaded components.⁽⁴⁾ 3M's diagnosis of the problem identified the temperature difference between the lead of the component and the land as the root cause of solder wicking. Delayed reflow and preheating the assembly before reflow were the proposed solutions. To delay reflow a solder composed of tin-lead and silver was formulated by adding 2% of silver to tin-lead solder, on the basis that silver containing solders contain sufficient oxides to slow their melting rate.

2.3. IBM

Solder wicking was identified as one of the most frequently occurring solder defects in the SMT area during the solder reflow process.⁽³⁾ Four possible causes were identified.

1. Contamination and / or oxidation of pad surface.

When a pad surface is oxidized, it inhibits wetting. This solderability problem of the pad tends to draw the solder away from the pad onto the component lead during reflow, thus creating a "starved" joint.

2. Solderability difference between component lead and pad

This has the same effect as oxidized or contaminated pad surface during reflow, resulting in an open solder joint.

3. Differences in thermal mass

Variation in heat transfer rate due to thermal mass differential creates a temperature gradient between the pad and the lead. This temperature gradient results in a time lag between the pad and the lead reaching the reflow temperature.

4. Variability in surface coating metallurgy of component leads.

In vapor phase reflow, where heat transfer is uniform, the heating rate is a function of both the thermal mass and thermal conductivity. Component leads with higher thermal conductivity and oxide-free surfaces have good solderability. On the other hand, by coating or plating the component lead surface with metals that form stable oxides, it is possible to slow down the wetting or spreading action of solder during reflow. For instance, SnPb coatings have better solderability than CuNi or CuFe coatings, because the oxide layer formed on CuNi or CuFe is not as easily removed as that formed on SnPb. In fact, IBM has used CuNi coatings on SMC leads to make the component lead relatively unsolderable, thereby reducing the time lag between the component lead and pad reaching the reflow temperature. IBM also suggests applying a thin coating of non-solderable materials such as epoxy or solder mask on the portion of the component lead above which solder is not desired to flow. This will serve as a solder dam preventing solder from wicking up the component lead.

2.4. Fujitsu

Fujitsu had also experienced solder wicking defects on PGAs during VPR soldering. Fujitsu implemented two methods that reduced, but not eliminated, solder wicking.

1. To delay the spreading of solder onto the lead of the PGA, one of the activators in the RMA flux was removed, resulting in the reduction of the wetting action of the flux on the component lead, thereby delaying the spreading action of the solder on the lead.
2. To reduce the spreading rate of the solder, Fujitsu also reduced the quantity of flux used for reflow soldering, and prebaked the assembly after fluxing, to minimize the spreading action of the flux up the component lead.

2.5. Other Companies

Depending on their specific assembly conditions, various electronics companies have deployed other techniques to resolve the solder wicking problem during VPR soldering. Some of the techniques included filing the component lead perpendicular to the direction of solder spreading so that the grooves on the lead can serve as solder dams.⁽⁷⁾ In some cases, a reduction in time difference of as much as 10 seconds was achieved between the lead and the land in reaching the solder melting point, by changing the orientation of the assembly during reflow.⁽⁸⁾ In fact, experimental results have shown a significant difference between in-line and batch vapor phase reflow soldering. Where in-line vapor phase soldering may cause open joints due to solder wicking, batch soldering showed no wicking at all. The cause of this difference was found in the angle of elevation of the board during the first stages of wetting. This angle is approximately 10^0 in the in-line system and allows the condensed fluid to flow off the board, leaving only a thin layer of fluid on the board. In the case of batch soldering, the boards are soldered in an almost horizontal position, causing the fluid to form a layer of approximately 1 mm thickness. This increases the heat contact between the lead and the land, thus reducing thermal gradients. Evaluation of boards placed at an angle of 10^0 to 15^0 in a batch system showed that solder wicking occurred in this case.

2.6. Discussion

To a degree, the root causes identified and the solutions provided by the various companies have general applicability in most eutectic tin-lead soldering processes. However, these solutions are not always applicable to all causes, due to the following reasons:

1. Changing the solder composition, like TI did, or adding 2% of Ag to the SnPb lead solder to delay reflow as 3M did, is not always possible due to varied specification requirements. In addition, formulating a solder alloy that has a delayed reflow effect and one that meets specification requirements could be very costly.
2. IBM's technique is workable only if the plating thickness of the coating material does not affect the lead size dimension requirements. In fact the method of plating the PGA lead with CuNi was attempted at Amdahl. But because the lead spacing of the PGA was so critical, the slightest increase in the lead thickness created shorts due to solder bridging during reflow. In addition the difficulty associated with maintaining uniform plating thickness from lead to lead, relative to the small lead size, was found to be extremely difficult. The use of non-solderable materials such as epoxies are generally applicable. But again, when the PGA lead density is high, with a narrow lead spacing, it can be extremely difficult to place the epoxy without creating a bridge between the leads. This bridging has the potential to create short circuit failure in the long run, especially if some electronic dirt starts to accumulate on the epoxy surface.
3. Removing one of the activators in the flux, as was in the case of Fujitsu, to reduce solder wicking is applicable only in areas where it is possible to change the flux

composition or type. This option is not always viable, especially if there are side effects associated with cleaning the assembly.

All the aforementioned solutions, provided to resolve the solder wicking problem by various companies, were basically tailor-made to the specific situation encountered by each company. Though some of the solutions have broad applicability, none of the methods has either the adequacy or the universal applicability to solve the problem of solder wicking effectively and economically.

CHAPTER 3

THEORY OF SOLDERING

Soldering is a well known joining method that has been used in most electronics products for many years. In its basic form, the soldering operation consists of the relative positioning of the parts to be joined, of wetting the surfaces with molten solder, and allowing the solder to cool down until it has solidified. But, many factors influence the outcome of the soldering operation, especially the components or parts to be joined and the soldering process itself. For soldering in electronics, tin-lead alloys with a melting point of about 185°C are the most often used. Therefore a clear understanding of the theory behind soldering in general, and tin-lead solders in particular, is paramount to comprehending and evaluating solder joint failures. In this Chapter, a comprehensive analysis of the soldering system, including a mathematical model of wetting forces and the concept of surface tension, is provided, starting with a brief discussion about phase diagrams in general and tin-lead solder in particular.

3.1 Phase Diagrams

Solder is an alloy that is used as a filler metal to form a metallurgical bond - one in which metallic continuity from one metal to the other is established. In general, soldering is a metallurgical joining method using a filler metal (the solder) with a melting point below (315 °C).⁽⁹⁾

In order to understand the property of an alloy in general, and solder alloys in

particular, it is necessary to know some of the basic transformations that take place within the alloying system, as a function of temperature and compositional changes. Much of the information about the control of the phase structure of a particular alloy system is conveniently displayed in phase diagrams, also termed an equilibrium or constitutional diagram. Phase diagrams are graphic representations of the relationships between constraints (temperature, pressure, and composition), and regions of phase stability, ordinarily under conditions of equilibrium. Phase diagrams provide us with the information necessary to determine the existence of intermetallic compounds, melting points of metals and their alloys, the solubility of one metal in other metals at different temperatures, and the compositions of various phases.

3.2 The Lead-Tin Phase Diagram

Since most soldering alloys are binary alloys of tin and lead, and most of the work in this investigation is focused on tin-lead solder, an investigation of this alloy system is necessary. A phase diagram for the tin-lead system is shown in Figure 2. Solder alloys used in the assembly of printed circuit boards are mainly composed of tin and lead in a ratio close to the eutectic point. The active constituent in most soft solders is tin, which promotes wetting of the majority of common metals; in many cases, the wetting is accomplished by the formation of layers of intermetallic compounds at the solder-substrate interface.

The *eutectic composition* is a distinct alloy that has a single melting or solidification point rather than a melting range. The melting point of the eutectic is always less than that of the individual constituent metals. In the tin-lead phase diagram of Figure 2, the eutectic point is marked as 61.9 percent tin and 38.1 percent lead, although the 63/37 composition is accepted in the electronics industry as the eutectic. Compositions other than the eutectic

do not solidify immediately upon cooling; instead, they have a temperature range in which

Figure 2. A simplified tin-lead phase diagram.(10)

they are partly liquid and partly solid. This region, often called the *plastic* or *pasty* range, becomes more pronounced the farther one moves away from the eutectic. In the plastic range, tin-lead solders have no strength. Even at temperatures of 30°C below the eutectic they are considerably weaker than they are at room temperature.(10) Alloys at or near the eutectic are therefore the most desirable for soldering. This is why the 63/37 and 60/40 percent ratios have been accepted in the electronics industry as being the most reliable tin-lead alloy.

The 63/37 and the 60/40 tin-lead solders, with their excellent mechanical, metallurgical, thermal, and electrical properties, meet most requirements for solder to be used for attaching and bonding leaded and leadless components to printed circuit boards. However, the 60/40 tin-lead solder with its plastic range between the solidus and liquidus points can cause disturbed joints, created by movement of the solder in the joints while still in the soft, pasty state. In addition, the 60/40 tin-lead solder was found to be more viscous and sluggish, with a shorter wicking distance, than the 63/37 tin-lead solder, which has a lower viscosity and better flow properties.⁽¹⁰⁾ The lamellar microstructure formed by 63/37 tin-lead solders is shown in Figure 3.

Figure 3. Microstructure of Eutectic tin-lead solder (63/37) X400 magnification. Note the fine intermixed structure of dark lead-rich α particles and the light tin-rich β particles. This is a typical eutectic structure.

Figure 4 is an engineering version of the tin-lead phase diagram. The melting temperature of the solder alloy is very important in many materials selection considerations. However, an alloy cannot necessarily be soldered at its melting point. At or slightly above its melting temperature the alloy is still sluggish, does not flow very easily, and seems to have some restraint in its wetting characteristics. Therefore in the case of tin-lead solders, the use of an approximately 38°C thermal gradient between the melting point and the soldering temperature of the alloy is generally recommended.⁽¹³⁾ It is usually good practice to start with as low a soldering temperature as possible and raise it only when necessary.

Figure 4. Engineering version of the tin-lead phase diagram.⁽¹⁴⁾

Another important factor that needs to be considered is the temperature of the soldering tool. The temperature any solder joint will reach during the soldering operation is the mean temperature, which lies between the temperature of the tools and that of the work piece and is the temperature that should be considered. This higher temperature is necessary to ensure proper flow of the solder and also to account for heat losses to the surface being soldered.

In soldering, the solder alloy goes through a complete cycle, from a solid to a complete liquid and back again to a complete solid. Depending on the composition and the phase changes, the properties of the joint can vary. For eutectic solders a total change from solid to liquid takes place at a temperature of 183°C . Again, once the solder is cooled and the joint is made, a complete change from the liquid to the solid takes place at the same temperature. However, in the phase diagram the important element of *time* is not considered. If a hot soldering iron (large heat source) is used to melt a drop of solder (small mass), the solder will melt and heat up to a high temperature within a short time and once the soldering iron is withdrawn the small quantity of solder will cool down in a relatively short time. However, a big solder pot containing a large mass of solder will take a longer time to heat up past the solidus and liquidus temperatures, and will also require a longer time span to cool.

When a solder joint is formed between two parts, it means that a specific interaction has taken place between the liquid solder and the solid surface of the parts to be soldered. For a solder joint to form a good intermetallic bond between surfaces, the solder should be able to wet these surfaces. This spreading effect of the molten solder along the base metallization surfaces, to produce complete and uniform solder coverage, is called wetting,

which is essential for soldering. In the next section, the concept of wetting and its implications on soldering are discussed.

3.3 Wetting

The term "wetting" is often used when discussing the soldering process. The ability of molten solder to flow or spread during the soldering process is of prime importance for the formation of a proper metallic bond. The phenomenon of spreading is usually referred to as wetting. By definition, wetting is a measure of the ability of a material, generally a liquid, to spread over another material, usually a solid. Wetting also refers to how well a liquid spreads on a solid surface and the more the spreading, the better the wetting. A measure of wetting is indicated as the change in area of, say, the liquid phase, or it is measured by the angle that a liquid makes with a solid surface. This is usually referred to as the contact angle. Contact angles of 180° and 0° correspond to the limiting cases of no wetting and complete wetting, respectively, as shown in Figure 5. In general, if the wetting angle (θ) lies between 0° and 90° the system is said to wet, and if θ is between 90° and 180° the system is considered to be non-wetting.

Ultimately, it is the nature of the surface forces that determine the ability of a liquid to wet a solid surface. As far as the soldering process is concerned, it is of interest to know what the conditions are that promote wetting. In soldering, this depends on the alloy and surface being soldered. For example, in soldering on a copper substrate, wetting could refer to the ability of the solder alloy to form an intermetallic compound with the copper. However, sometimes it is desirable to have the apparently contradicting situation of a molten alloy with good wetting characteristics to produce a good bond but also have restricted flow.

Figure 5. Relationship between Contact angle, θ , and extent of wetting.

The most fundamental characterization of wetting is given by considering the thermodynamics of the wetting process. The melting and wetting of molten solder on a metallic substrate is not an equilibrium process. It is an irreversible, non-equilibrium process. The solder cannot "dewet" or contract due to small changes in the process variables such as pressure, volume, or composition. Furthermore, for tin-lead solder spreading on copper, the formation of the tin-copper intermetallic is a kinetic process and depends on time.

According to thermodynamics, the free energy change, denoted by ΔG , can tell us whether a process will occur spontaneously under some given conditions. In particular, the sign of the free energy change between the two states is an indication of the direction in which the process will occur spontaneously. Thermodynamics tells us that the process is possible but gives no information about the rate at which the process may occur. If the change in free energy is zero ($\Delta G = 0$), then the system is at equilibrium and remains so unless the conditions are changed.

For a process at a constant temperature and pressure, the free energy change can be equated to the enthalpy (heat) change during the process, if the entropy change is assumed to be zero. Since no gaseous species are involved in the reactions of concern here, this is a reasonably good assumption. An equivalent way of saying that the free energy must decrease for a spontaneous process is to say that the process must be exothermic, that is, heat must be liberated. As related to the soldering process, if there is a net result of a natural attraction between the surface atoms of the solder and the surface atoms of the substrate, then this is a stabilizing process providing liberation of heat. In terms of free energy, good wetting will occur if there is a great difference in the surface free energy between the two substances, because the result is a net lowering of the total free energy. That is, the surface energy of the solder is lowered by it forming an interface that is at a lower surface interfacial energy.

An elementary result of thermodynamics is that at constant temperature and pressure, the free energy represents the net work of the system and this net work can be related to other more basic variables of the system. For example, if the surface area of a liquid changes by an amount ΔA , then the work involved is:

$$W = \Delta A \cdot \gamma \quad \text{[Equation 1]}$$

where

W = work involved in changing the surface area,

γ = surface tension of the liquid

The *surface tension*, usually denoted in units of force per unit area (dyne/cm) is actually the specific surface free energy (dyne.cm/cm²)

In the case when

$\Delta A = 1 \text{ cm}^2$, then

$$W = \gamma \quad [\text{Equation 2}]$$

and the surface tension is the work required to expand a surface by a unit area.

By using the fact that the free energy change represents work, one can relate the free energy change to surface tension as follows:

$$dG = d(\gamma A) = A d\gamma + \gamma dA, \quad [\text{Equation 3}]$$

If γ is a constant, then we obtain

$$\Delta G = \gamma \cdot \Delta A \quad [\text{Equation 4}]$$

For a system that consists of molten alloy (A), a substrate (B) and an interface (AB), the work of adhesion, W_{AB} , is as follows:

$$W_{AB} = \gamma_A - \gamma_B \quad [\text{Equation 5}]$$

where

γ_A is the surface tension of A,

γ_B is the surface tension of B, and

γ_{AB} is the interfacial tension between the two.

The work of cohesion, W_{AA} , is given by:

$$W_{AA} = \gamma_{AA}. \quad [\text{Equation 6}]$$

For spontaneous spreading or wetting, the work of adhesion should be greater than

the work of cohesion, i.e.,

$$W_{AB} > \gamma_{AA} \quad \text{[Equation 7]}$$

This is obtained if the liquid A has a lower surface tension than the solid surface. Thus, it is not sufficient just to say that there should be a significant difference in the surface energy of the liquid and solid. A liquid with a high surface tension does not promote wetting.

Though thermodynamics provides some insight into the phenomenon of wetting, it is still difficult to explain or predict the exact properties desirable in a flux, metal, or substrate. Oxides and metal surfaces have surface free energies on the order of 500 to 5000 ergs/cm². Based on surface energy alone it would be difficult to account for the wetting behavior of solder on metal surfaces. For the wetting of solder on copper, the dominant force is most probably the formation of intermetallic compounds. Flux plays an important part in enhancing the ability of the solder alloy to form an intermetallic compound by removing tarnish (oxide films) formed on the metal surface. The flux may also play a role in reducing the surface tension of the solder and thus reduce the work of cohesion, i.e., a flux can act as a surfactant. The purpose of the flux is to clean the surfaces to be soldered of any oxides that may have formed, but flux cannot overcome poorly prepared substrates or components. The existence of grease or any other contamination on the surface of the metal is detrimental to wetting.

The mutual solubility of the solder alloy and the substrate is related to the wetting process.⁽¹⁵⁾ The greater the solubility of the metal in the solid state, the lower the interfacial energy will be when these metals are brought into contact with one another. But it is not guaranteed that a solid metal will be wetted by another liquid metal if the two metals are fairly soluble in one another.

3.4 The Soldering System

The basic soldering process depends on wetting for the formation of a solder-to-base metal contact. It is this physical wetting by the molten solder that generates the fundamental requirement for joining interfaces. As shown in Figure 6, when two metal parts are joined by solder, metallic continuity is established as a result of the two interfaces where the solder is bonded to both metallic parts. There are at least two such bonds in each joint, the solder serving both as a bond maker and as a link in the metallic continuity.

Under standard conditions, both the base metal and fusible solder alloy have a thin film of tarnish on the surface.⁽⁹⁾ This interferes with the formation of the interface. These nonmetallic corrosion products act as a barrier to the formation of metallic continuity in a solder bond and must be removed. If the surfaces are clean and their metal atoms are thus

Figure 6. Two metals bonded by solder

positioned immediately at the interface, wetting takes place and the solder flows across the surface. The solder atoms are now able to come sufficiently close to the atoms of the base metal and can form an alloy at the interface, thus ensuring good electrical contact and good adhesion. The removal of these nonmetallic films is one of the primary functions of fluxes.

Assuming a perfectly clean metallic surface, and that no re-oxidation or other environmental attack occurs, there are three elements necessary to obtain the basic interface

between the solder and base metal. These three elements are the solder metal itself, the base metal, and either the flux or the atmosphere (air or vapor) in which the process takes place. At soldering temperatures, the base metal, which has a relatively high melting point, is solid. The fusible solder alloy is liquid, and the flux is usually a liquid, although it can also be a gas. To provide the reader with a basic understanding of the various wetting forces and their interaction in the soldering system, a model representing the general soldering system is exhibited in Figure 7. With reference to Figure 7, consider a drop of liquid solder resting on a metallic surface in the flux atmosphere.

Figure 7. Model of thermodynamic equilibrium in wetting.⁽⁵⁾

In effect, we have a three component system of a solid (S), a liquid (L), and a vapor (V).

Then,

$$\gamma_{sf} = \gamma_{ls} + \gamma_{lf} \cos\theta \quad [\text{Equation 8}]$$

where,

γ_{lf} = surface tension between the liquid solder and the flux acting at a tangent to the liquid curvature.

γ_{sf} = interfacial tension between the solid base metal and the flux.

γ_{ls} = interfacial tension between the liquid solder and the base metal

When gravity is negligible, which is the case with small droplets, the shape of the droplets is determined solely by the three surface tensions. As every system tends towards minimum free energy, the areas of the interfaces and the free surfaces tend to become as small as possible. In doing so, however, they counteract one another, the reduction of one area leading to the enlargement of another. The droplet selects that shape for which the total surface free energy, $F_{surface}$, has a minimum value.

At the point of total thermodynamic equilibrium, with no further diffusion or chemical reaction, the system will have an interface at which all three phases meet. If we consider the plane perpendicular to the interface, we can see that the three phases meet at a certain angle to each other. This angle, θ , formed between the liquid and the solid is called the *dihedral angle* or the *contact angle*.

Again, consider the balance of vectors at point A in Figure 7, where the three forces meet. The three forces are actually the surface energies that brought this system to equilibrium. Here γ_{sf} is the force which spreads the liquid on the solid, i.e., *the spreading or wetting force*. Spreading or wetting will occur if γ_{sf} is larger than $(\gamma_{ls} + \gamma_{lf} \cos \theta)$. Wetting or spreading can occur only when the contact angle θ between the liquid and the solid surface is less than 90° . Therefore the system will be in equilibrium only when:

$$\gamma_{sf} = \gamma_{ls} + \gamma_{lf} \cos \theta \quad [\text{Equation 9}]$$

$$\text{and} \quad \cos \theta = (\gamma_{sf} - \gamma_{ls}) / \gamma_{lf} \quad [\text{Equation 10}]$$

where θ varies from 0° to 180° .

Based on the above equations, for an equilibrium condition the surface tension of the solid must be greater than the surface tension of the interface and the surface tension of the liquid-solid interface must be greater than the difference between the surface tensions of

the solid and the liquid. When the contact angle θ approaches 90° , then $\gamma_{sf} = \gamma_{ls}$ and the interfacial tension becomes zero.⁽¹⁶⁾ The fact that the liquid solder wets the metal, displacing the flux, indicates that $\gamma_{ls} < \gamma_{sf}$ and that no equilibrium will occur as long as there is enough solder.

The analysis of the surface tensions in the soldering system is based on the assumption that the wetting parameters do not change and that the values of the surface tensions are constant. But in practice equilibrium is seldom achieved during soldering. The factors that need to be considered in practical soldering processes are as follows:

1. The contact angle is a function of the liquid flow property. A receding liquid has a different contact angle from a spreading one. In the tin-lead-copper system, for example, it was empirically observed that the contact angle of spreading is greater than that of receding.⁽¹⁷⁾ A wetted surface can never become a clean surface again, because the diffusion layer formed affects the nature of the interfacial tensions.
2. The contact angle is also dependent on the surface condition of the solid. Spreading over a rough surface exceeds spreading over a smooth surface.⁽¹⁸⁾
3. The rate of wetting increases with a rise in temperature of the system because temperature affects both wetting and surface tension of the system. At a certain temperature (*critical temperature*), which is unique for each system, a sudden increase in wetting occurs.
4. The cohesive force of the liquid, the measure of the affinity of the liquid for itself, is a restraining force to spreading because it acts to decrease the surface area.

5. During soldering the flux performs its cleaning action, by which the surface, and the existing surface tension, changes. If the flux is exhausted or flows away, re-oxidation takes place, again changing the wetting conditions.
6. In most practical soldering operations the operation is completed before thermal equilibrium is reached. If temperature variations exist, the liquid solder tends to flow in the direction of the highest temperature because in general at a high temperature the surface tensions are lower.⁽¹³⁾

3.5. Flux and Soldering

In soldering operations, fluxes have important chemical, thermal and physical functions. The *chemical function* of fluxes is to react with surface tarnish films, such as oxides and sulfides. The reaction products are then displaced by the molten solder which is able to wet the exposed, clean metal surface. The flux also functions as a chemical blanket by preventing and protecting the cleaned surface against re oxidation. In order to be able to clean the metallic surfaces chemically, the flux should be able to wet both the base metal and the solder surfaces. This means that the flux has to displace any layer of air or tarnish on the solid surface, creating a temporary bond with the metal. This phenomenon provides a tarnish-free surface and keeps the surface in a clean state.

The *thermal function* of fluxes is to assist in the transfer of heat from molten solder to the joint area so that the base metals reach a high enough temperature to be wetted by the solder.

The *physical function* of fluxes is to reduce the interfacial surface tension between

the solder and the base metal, enabling the solder to flow over and metallurgically wet the solderable surface. The presence of flux in the soldering region affects the surface-energy equilibrium in favor of solder spreading because flux can be displaced easily by liquid solder. This ability of flux to promote wetting is called *flux efficacy*.

Flux activity is defined as the degree of efficiency with which a given flux promotes wetting of surfaces by molten solder. This is a function of the activator in the flux, and temperature, and volume of flux vehicle. The flux activator enables the flux to remove oxide from the metal surfaces to be soldered. The more chemically active the flux activator is, the more effective the flux is in cleaning metallic surfaces. This role of the activator is in turn dependent on temperature. Generally, flux activity increases with temperature rise. Usually most fluxes are inactive at temperatures below room temperature.

The flux vehicle is composed of solids, nonvolatile liquids, or a combination of both. The vehicle serves three functions: (1) it serves as a high temperature solvent for materials formed in the reaction between the surface oxide components and the activators; (2) it serves as a blanket to prevent re-oxidation of the surface cleaned by the activator; and (3) it serves as a heat exchange medium to aid in rapid heat transfer to the surfaces being soldered. During the soldering process the volume of the flux vehicle affects the wetting time. In a laboratory experiment conducted by Polczynski and Seitz, a reduction in wetting time was observed with an increase in flux volume.⁽²⁰⁾

3.6. Effect of Surface Texture

Surface texture has a direct influence on solder spreading activity.⁽¹⁵⁾ For example, if the real solid surface area is larger by a factor f than the apparent geometrical area, because of the roughness of the surface, then Equation (7) must be modified as follows:

$$f (\gamma_s - \gamma_{ls}) = \gamma_{lr} \cos\beta \quad [\text{Equation 11}]$$

in which β is the apparent contact angle. When the contact angle on the completely smooth surface with the same wetting properties would be θ , it is found that

$$\cos \theta = f \cos\beta \quad [\text{Equation 12}]$$

This means that in order to meet the condition of wetting θ must be less than 90° and therefore, $\beta < \theta < 90^\circ$. Under this condition the solder will spread or wet more on the rough surface that has a lower contact angle value, β , than on the smooth surface. The influence of surface texture is also dependent on the nature of the roughness. Grooves on horizontal plates can act as capillaries lengthwise and the spreading will stop only when the solder has been fully consumed. Grooves that are perpendicular to the direction of spreading will act as barriers, because in every groove a position may be found where the contact angle assumes a critical value. The spreading in the sideways direction is especially hampered when the hills between the grooves have a sharp edge. In practice, the spreading will no longer increase if the average surface roughness is increased above $150 \mu\text{m}$.⁽²⁰⁾

Some of the most important parameters thought to be critical to the soldering system, and their effect on solder joint formation, were discussed in this chapter. A mathematical model of the system and the forces that influence soldering was also described. This basic understanding of the soldering system is important to understand and differentiate the various soldering methods discussed in Chapter 4, which will focus on vapor phase reflow soldering and the phenomenon of solder wicking.

CHAPTER 4

SOLDERING OF SURFACE MOUNTED COMPONENTS

Introduction

The solder used in the electronics assembly process serves to provide electrical and mechanical connections. In Printed Through Hole (PTH) assemblies the main concern is restricted to obtaining sound electrical connections, because the plated through holes provide sufficient mechanical connection. However, in the case of SMT, the function of the solder joint has become very critical because it must provide both mechanical and electrical connections. Solder joint integrity, in the case of SMT, is controlled by two major requirements: *Coplanarity* of the leads of the component and the land area of the substrate and *Solderability*, or the ability of the solder used in the joining process to create a good metallurgical bond between the component and the board. Utilizing the correct soldering method and equipment determines the ability to successfully meet these critical requirements. One of the soldering methods used in SMT is reflow soldering.

4.1. Reflow Soldering - Theory

Reflow soldering is the making of joints by remelting previously applied solder, without the addition of any extra solder during the soldering process. Thus, when two pretinned surfaces are reflowed and brought into contact simultaneously a solder joint can result, provided that the tarnish layers on top of the molten solder are removed or broken up. The principle behind reflow soldering is simple. Two presoldered parts to be joined are

brought into intimate contact. The temperature is elevated above the melting point of the solder, at which time it wets the metallic surfaces. When the temperature is lowered, the solder solidifies, completing the joint. Generally, there are three major requirements in reflow soldering.

1. The reflow temperature of the solder alloy must be compatible with the metallization used on the components, the substrates, and the reflow system. This means that the solder alloy melts at approximately the same temperature as the solder coatings on the component leads and substrate lands. Also, the constituents of all three must not form undesirable intermetallic compounds, with brittle or weak mechanical properties or high electrical resistance.
2. The surface tension of the molten solder should be sufficiently strong to provide a continuous surface between the component lead and the land on the board during the reflow process, thus resulting in fillet formation upon cooling. The surface tension of the molten solder is what makes surface mounting a manufacturable process. It is extremely difficult and costly to form component leads into an absolutely planar arrangement. Therefore, a soldering system (solder alloy, flux, solvent, and reflow technique) that can provide a measure of compensation for non-planarity is very desirable and valuable.
3. The strength of the alloy formed after the reflow soldering step must be strong enough to provide reliable joints. The properties of the joint (flexibility, strength, rigidity) are dependent upon the choice of the alloy constituents. It is also critically affected by the time, temperature and reflow operation.

4.2. Reflow methods and equipment.

Currently several techniques for reflow soldering are in common use. Those most frequently used in production processes are described below.

4.2.1. Thermal Conduction

One of the oldest reflow techniques is the application of heat by way of thermal conduction. In its simplest form this consists of nothing more than a hot soldering iron applied to previously deposited solder. Slightly more sophisticated is the temperature controlled hot plate: the board to be soldered is manually positioned on the hot plate until the solder is observed to melt; it is then manually removed and allowed to cool. The most elaborate equipment of this type employs conveyors to automatically transport the assembly across the plate, followed by a cooling section to allow the solder to solidify. Lack of temperature controllability, excessive oxidation and low throughput are some of the disadvantages of this process.

4.2.2. Thermal Convection

Reflow by thermal convection is another approach with a long established history. In this method, heated air serves as the thermal transfer medium. An ordinary resistance heated oven is the simplest example of a convection reflow system. Boards must be manually loaded and unloaded into and from the oven. The slow heat transfer rate makes this method inadequate for mass reflow SMT processes that require high throughput.

4.2.3. Laser

In this approach, the energy from a high-power laser is directed onto the joint. Reflow can occur in a fraction of a second, but the process is relatively slow because each joint must be soldered individually. This is a special form of the direct radiation heat

transfer method for reflow soldering.

4.2.4. Infrared

Solder reflow by direct infrared (IR) radiation is a more recent development. The IR process primarily uses the transfer of heat by absorption of radiant energy. Unlike conduction and convection, radiation heat transfer does not require physical contact. Gases such as air and nitrogen are transparent to infrared radiation and do not play any role in pure radiation heat transfer systems. The major difficulty with IR reflow is that it is not an "equilibrium" method of heating, i.e., the heated object will never reach the same temperature as the heating source. With IR sources, to reach a maximum safe reflow temperature of 220°C, one must depend on accurate pulse operation of the heaters. In the case of a continuous SMT process, the belt speed must also be adjusted such that the heated object exits the heating chamber at the correct time and temperature.

4.2.5. Vapor Phase

Developed by Western Electric Company in the mid-1970s, Vapor Phase Soldering (VPS), also called Condensation Soldering, is a technique that was initially designed to solder Multilayer Board (MLB) assemblies. In this process, the assembly to be soldered is immersed into a body of hot saturated vapor; the vapor condenses on the relatively cold part and releases the latent heat of vaporization to heat the assembly. Because condensation heat transfer is rapid and relatively independent of part geometry, VPS has become the method of choice for high volume and high density PCB soldering.

4.3. Vapor Phase Equipment and Process

Vapor Phase soldering offers good temperature control, uniformity of heating, and excellent heat-transfer efficiency. It relies on the condensing vapors of the boiling liquid to

raise the temperature of the assembly to the boiling point of the liquid. A fluorinated hydrocarbon (FC- 70 or FC-5311) having a high boiling point, good heat stability, and oxidation resistance is used as the liquid. In its simplest form the soldering equipment is constructed as shown in Figure 8. The equipment is designed so that the boiling vapor, which is heavier than air, is retained within the confines of the equipment. When the system reaches equilibrium, the temperature of the vapor is equal to the boiling temperature of the liquid and this temperature is maintained until the cold work piece is introduced. All the surfaces of the work immediately act as condenser plates, and while the vapor reverts to the liquid state, it releases its latent heat of vaporization. The temperature of the workpiece rises to the boiling point of the liquid, when heat transfer stops. Since all surfaces are involved and the heat transfer is intimate, great economies can be achieved in a rather short time. Once the assembly reaches the soldering temperature, the workpiece can be slowly withdrawn from the vapor. The flux is washed off the surfaces, dried out, and is filtered from the heat-transfer medium as solid particles. The heat transfer medium can be used repeatedly until it is either dragged out or lost to the environment by poor operating techniques or standard diffusion losses.

4.3.1. Vapor Phase Reflow Process Phases.

Vapor Phase reflow soldering is a sequence consisting of three major phases, as shown in Figure 8. Each step is critical to the formation of a strong and reliable metallurgical bond.

Phase I: Preheat

The first phase, conducted in the preheat section of the machine, starts with solvent evaporation. The purpose of this process is to evaporate any trapped gases and eliminate bubble formation that can cause "blow holes" or voids during solder joint formation.

Figure 8. Schematic diagram of vapor phase reflow (VPR) unit.

Phase II: Wetting or Reflow

Here the flux melts and begins the chemical reaction with the metal oxides, preparing a "clean" metal surface for the solder. As this metal oxide reduction action of the flux is proceeding and the assembly moves into the reflow chamber, the solder spheres or solder bumps of the land begin to melt at the hottest spots, replacing the flux and wetting the clean lead surfaces. This wetting action results in the wicking of the solder onto the hottest and cleanest metal surfaces. The speed of the action depends strongly upon the fluxing action, the local temperature, and the metal alloys of the component lead, solder paste or bump and substrate.⁽²¹⁾ Under most conditions, temperature non uniformity is the major problem. The high temperatures reduce surface tension and can promote significant wetting and wicking action.

This is the stage where the solder completely melts. The heat source should be 25°C to 40°C higher than the melting, or liquidus, temperature of the selected alloy, to assure

complete melting of the solder and good metallurgical bond formation. The actual time for the solder to completely melt and wet the metals to be joined depends upon the localized temperature of the assembly. At a typical reflow temperature of 215°C (Sn63 or Sn62) it is generally 1 to 2 seconds.⁽²²⁾ For the case shown in Figure 9, the wetting time at 215°C is actually less than 1 second.

The time that the assembly is at the maximum temperature of the reflow system should be limited to approximately 30 to 50 sec,⁽²²⁾ depending upon the thermal mass of the assembly. This will allow reflow to take place, but will minimize the formation of undesirable intermetallics or damage to the board. This will also allow time for trapped flux and residual solvents to escape, thus minimizing void formation as the solder cools.

Figure 9. Plot showing the relationship between Wetting Time and Reflow Temperature.⁽²⁾

After all of the solder is melted, a liquid solder "volume" forms. The action of the surface tension of the molten solder then prevents further wicking action. Thus, the surface tension action, which minimizes surface area, is beneficial in that it helps hold the solder in place and bridge the gap between the component lead and the substrate, forming a fillet upon cooling down. The volume of solder, the metal alloys being joined, and the physical geometry of the metal (shape and space of the lead and land) determine the resultant shape, extent of fillet formation, and strength of the solder joint.

Phase III: Cool Down

The cool down after reflow should take place within 30 to 50 sec to enhance small grain formation but should be no greater than 3°C/second to prevent thermal shock damage to some of the components. The cooling rate of the solder joint after reflow is important because the faster the cooling rate, the smaller the grain size of the solder, thus leading to improved fatigue resistance. Larger grain sizes in solder usually promote void formation and joints that are weaker.

4.3.2. Heat Transfer Mechanism In Vapor Phase Soldering

Condensation soldering is a slow transient filmwise condensation heat transfer process.⁽²³⁾ When the assembly to be soldered enters the primary vapor zone, the vapor condenses on its surfaces, releases its heat of vaporization, and forms a thin, continuous liquid film. The heat transfer rate to the surface of any part at any instant is controlled by the general Newton's heat transfer equation.⁽²⁴⁾

$$Q = hA (T_v - T_s) \quad \text{[Equation 13]}$$

where Q = heat transfer rate from vapor to part (Btu/hour)

h = heat transfer coefficient (Btu/hour.ft².°F)

T_v = saturated vapor temperature (°F)

T_s = part surface temperature (°F)

A = product surface area (ft²)

h is determined by the thermal conductivity, viscosity, and density of the liquid condensate, and by whether the surface of a part is vertical, horizontal, or oblique.⁽²⁵⁾

It is apparent from Equation (13) that only the maximum surface heating rate and the maximum surface temperature of any part on a surface mount assembly can be controlled during VPS. The maximum surface heating rate of a part occurs when T_s is minimum, that is, when the part is initially immersed in the primary vapor zone. The initial T_s , hence the maximum heating rate of any part, can be controlled by preheating the part before immersion in the primary vapor zone.

The maximum surface temperature of any part will depend on the dwell time of the assembly in the vapor zone. With increasing part dwell time in the primary vapor, T_s will asymptotically approach T_v , and the heating rate will approach zero. Given sufficient dwell time in the primary vapor, the surface temperature of all parts of a surface mount assembly will eventually reach a maximum of T_v .

The dwell time of the assembly in the primary vapor zone is fixed by the conveyor speed in an in-line system and by the elevator speed and dwell time in a batch vapor phase system.⁽²⁵⁾ Figure 10A shows that when the dwell time is sufficient, the lead temperature reaches the maximum temperature of 215°C. As shown in Figure 10B, if the dwell time is

(A)

(B)

Figure 10 (A) Impact of long dwell time (2 min.) in the primary zone of a VPS on a PLCC lead temperature.⁽²⁶⁾
(B) Impact of short dwell time (10 sec.) in the primary zone of a VPS on a PLCC lead temperature.⁽²⁷⁾

too short, the surface of the component lead does not reach the maximum possible temperature. For successful soldering, it is recommended that all PCB land and component lead surfaces on a surface mount assembly reach a temperature 30 to 50°C above the melting point of the solder.

4.5. The Phenomenon of Solder Wicking

Vapor phase is the preferred mass soldering method for surface mount circuit boards of various styles and sizes composed of components with different shapes and thermal density.⁽²⁸⁾ However, it is still an emerging technology. As a result, it is affected by various problems that undermine solder joint quality. One of the most significant and common solder joint defects in vapor phase reflow soldering is Solder Wicking⁽²⁸⁾. *Solder wicking is the rise or wicking of solder up the vertical portion of a lead on a leaded component, resulting in an open or poor fillet at the substrate and component lead joint.* This solder joint defect results in both mechanical and electrical failures. Solder wicking can also be a costly defect particularly in reflow soldering processes where the amount of solder per joint is limited.

4.5.1.Theory of Solder Wicking

To understand the solder wicking failure mechanism in reflow soldering, and to identify the critical factors that govern this phenomenon, an in-depth understanding of the interactions of the various wetting forces during reflow soldering of a PGA is necessary. Figure 11 is a schematic representation of the wetting forces during reflow soldering of a PGA. From Young's theory, the lead wetting force, L_f , is given by:

$$L_f = \gamma_{lf} - \gamma_{ls} + (\gamma_{sf} \cos\theta) \quad \text{[Equation 14]}$$

Figure 11. Schematic Diagram showing the wetting forces that exist during vapor phase reflow soldering of a PGA

and the pad wetting force, P_f , is given by:

$$P_f = \gamma_{pf} - \gamma_{ps} + (\gamma_{sf} \cos \beta) \quad [\text{Equation 15}]$$

For solder wicking to occur, the vector sum of the net lead wetting force, L_f , must be greater than the vector sum of the net pad wetting force, P_f . In order to focus on the problem of solder wicking, one can ignore the issue of wetting, and rewrite Equations 14 and 15 in the simplified form shown in Equations 15 and 16.

$$L_f = \gamma_{lf} - \gamma_{ls} \quad \text{[Equation 15]}$$

$$P_f = \gamma_{pf} - \gamma_{ps} \quad \text{[Equation 16]}$$

This indicates that the net difference between γ_{lf} and γ_{ls} , and between γ_{pf} and γ_{ps} , plays a critical role in the rising of the solder up the lead. The magnitude of these interfacial tensions are affected by a number of variables, including material type, temperature and thermal mass.⁽²⁹⁾

Vapor phase reflow heats up all surfaces relatively fast; heat transfer to the surface of a material is therefore constant regardless of its composition or geometry. Therefore, the rate of heating is dependent on the mass and thermal conductivity of the material being heated. Generally, metal leads have low mass and high thermal conductivity relative to the pad of an assembly, and therefore they heat up faster. This will lead to a temperature difference between the pad, which is relatively insulated and located on the circuit board, and the lead, which is directly exposed to vapor condensation. In soldering, the rate of wetting increases with a rise in temperature. This relationship is nonlinear and *below a critical temperature*, which is unique for each system, *wetting forces are very weak* while *above* it they are *strong*.⁽²⁾ During vapor phase reflow, molten solder is exposed to the lead at a temperature above the critical region and to the pad at a temperature below the critical region.⁽²⁾ Under these conditions, the solder will preferentially wet the lead rather than the

pad. The solder in contact with the lead will melt first, drawing the molten solder away from the pad, causing most of the solder to wick up the lead. As shown in Figure 12, failure of the solder to return to and wet the pad will result in an open or starved joint.

Figure 12. A wicked solder joint on a vapor phase reflowed PGA.

This wicking action is also strongly influenced by the pad solderability, the lead surface texture, and the amount of flux present in the soldering system. When a pad surface is badly oxidized, or has relatively low solderability, it inhibits wetting and solder is drawn away from the pad. On the other hand, a rough surface finish enhances solder wetting up to a point. The wicking action of solders is further increased in the presence of flux, because the flux not only assists the wetting /wicking action, but it also serves as a heat transfer medium. These actions of the flux are also a function of the amount of flux available in the soldering system.⁽²⁰⁾

Generally, the same factors that affect the formation of a good metallurgical bond, as discussed in Chapter Three, also affect the formation of solder wicking in vapor phase

reflow. These factors are solder alloy type, soldering temperature and time, flux amount, and lead surface texture. The role each factor plays in vapor phase reflow soldering in general, and solder wicking in particular, is discussed in the sections that follow.

4.5.2. Preheat

Generally, preheating assemblies before soldering is performed in order to activate the flux, evaporate the flux solvent, remove the volatile constituents of the solder paste, and prevent thermal shock to the assembly. However, the most important reason for preheating is to heat the lands on the board sufficiently so that, combined with the additional heat supplied during soldering, the solder has a chance to form an equilibrium fillet shape before it freezes.⁽³⁰⁾ In vapor phase reflow soldering, preheat plays two critical roles.

1. If a low-boiling solvent fluid is used to provide a secondary vapor blanket, then heating the assembly above the fluid's boiling temperature before it enters this zone will prevent vapor condensation that can rinse away the flux prematurely.
2. Preheating the assembly to just below the solder solidus temperature minimizes the temperature gradient between various parts of the assembly having different thermal mass, thus reaching the time needed in the reflow zone where solder wicking occurs. In fact, reducing the temperature difference between the land and the lead by preheating the assembly has reduced the heating rate differential between land and lead from 16 seconds to 10 seconds,⁽³¹⁾ as shown in both Figure 13 and Figure 14.

4.5.3. Flux

The rate of wetting action of the solder is dependent on both the rate of heating of the specimen and the rate of cleaning of the surfaces by the flux.⁽³²⁾ In vapor phase reflow

Figure: 13. Without preheat during VPS, the lead and the land of a PLCC reach the solder melting point temperature (183°C) 16 seconds apart.⁽³²⁾

Figure: 14. With preheat during VPS, the lead and the land of a PLCC reach the solder melting point temperature (183°C) 10 seconds apart.⁽³²⁾

soldering, the presence of flux enhances wetting by creating a clean metallic surface, by influencing the surface tension forces in the direction of solder spreading and by facilitating heat transfer. Unfortunately, if the right amount is not used, this role of the flux has also the potential of enhancing solder wicking during the reflow process, if a significant temperature gradient between the land and the lead exists..

4.5.4. Reflow time and temperature

As discussed earlier, and illustrated in Figure 13, the surface of the lead reaches the melting point of the solder 16 seconds before the surface of the land, during vapor phase reflow soldering of PLCCs. This causes the solder paste to melt, wet, and wick up the lead before the land becomes hot enough for the molten solder to wet. This indicates that in the presence of a temperature differential due to differences in thermal mass, the reflow temperature and dwell time of the assembly in the reflow zone become critical factors in creating solder wicking.

4.5.5. Lead surface texture

Lead surface finish is another critical factor that enhances solder wicking especially when combined with the various factors discussed above. In Chapter Three, it was shown that rough lead surfaces in general enhance solder spreading and wetting action.

In order to prevent solder wicking and to make the reflow soldering process robust to solder joint defects, it is necessary to optimize and control the critical vapor phase reflow parameters discussed in this chapter. In the next chapter the experimental approach taken to investigate and resolve the solder wicking problem is discussed.

CHAPTER 5

EXPERIMENTAL PROCEDURE

Introduction

Optimizing the reflow soldering process was the approach taken to address the solder wicking problem in PGA assemblies. This encompassed two critical steps, namely, process characterization and optimization. Process characterization is a method of identifying important input variables that affect the process output or response. Process optimization is identifying the region within the important variables or process parameters that leads to the best possible response or output. This task was accomplished by performing a sequence of three designed experiments corresponding to the various stages of the soldering process, namely (1) PGA tinning or pre soldering characterization experiment, (2) PGA tinning process optimization experiment, and (3) PGA mounting and VPS reflow soldering experiment.

5.1. Design of Experiments

In the most general sense, an experiment is defined as a "considered course of action aimed at answering one or more carefully framed questions."⁽³³⁾ A designed experiment is a test or series of tests in which intentional changes are made to input variables of a process or system so that the reasons for changes in the output can be identified. The underlying idea of a statistical experiment is simple. Assume that it is required to estimate the output (response) of an unknown system. Although the relationship between output and inputs (response surface) is unknown, it can be locally approximated by a polynomial (for example Taylor expansion).⁽³⁸⁾ By adding observations to an

experiment, it is possible to increase the precision of the approximation but at the cost of a larger experiment.⁽³⁹⁾ If a first order approximation is sufficient, it provides the standard linear model familiar from Analysis of Variance(ANOVA) and regression analysis.

However, the factors and the functional form (i.e., number of factors of the polynomial) of the response or output are specified by the designer, based on experience and engineering judgment. This has two implications. First, if prior perceptions are incorrect, the model is wrongly specified. If there are omitted variables correlated with other variables in the model, the estimate will be biased. Second, if the designed experiment does not fully incorporate all combinations of factors and levels (i.e., if the experiment is less than full factorial), some omitted factors may be confounded with the factors under consideration. This implies that the success of a designed experiment is not only dependent on the accuracy of the design, but also on knowledge and experience of the designer about the system in question.

In Chapter Two, the different approaches taken by various industries to resolve solder wicking solder joint defects were discussed. It was also indicated why these methods were found to be inapplicable to this particular investigation, due to the unique manufacturing process, and material, cost and time requirements and constraints. Therefore, based on the process requirements and considerations, a designed experiment was identified as the method of choice to investigate and resolve the solder wicking defect.

5.2. General Approach

A sequence of three experiments corresponding to the PGA assembly process stages was performed to identify the causes of solder wicking defects and to optimize the soldering system. A complete description of the PGA mounting process is provided in

Appendix A. Theoretical analyses and process quality data indicated that solder wicking defects occur both at the mounting and tinning / pre-soldering process stages. Experiment I was a pre-soldering or tinning process characterization experiment. Experiment II was conducted to optimize the pre-soldering process. Experiment III was performed to optimize the vapor phase reflow soldering process. The approach for each experiment was as follows:

1. To define the requirements for the experiments, a multi-disciplinary team from design, engineering, test and production was established.
2. An evaluation of the experimental results and analyses was conducted at the end of each experiment before the next one was begun.
3. Visual inspection of the test coupons was performed by two trained operators. Defects were recorded using the standard production inspection rule. The use of different inspectors highlights situations where the inspector may unintentionally induce bias in the results which were in general very robust to the different inspectors chosen.
4. An average of 20,000 solder joints or leads were inspected for each experiment. This implies a considerable probability of making mistakes. In order to reduce the probability of mistakes, all test samples were randomized and inspected a second time. Possible inconsistencies in the results were addressed by performing a third inspection.
5. The results were analyzed using Analysis of Variance (ANOVA).

5.3. Experiment I

The objective of this experiment was to identify and characterize the critical parameters, or factors, in the tinning process that could contribute to solder wicking defect generation. Based on knowledge of the theory and the process, the following factors were considered important to the solder wicking problem during tinning:

- A. *PGA lead surface texture/roughness.* There are several process steps (e.g., removing PGA from package, removing PGA from tinning jig and/or lead straightening process), where the surface of the PGA lead may be scratched.
- B. *Baking or preheating time.* PGAs are baked in an oven for 20 minutes, after fluxing and prior to tinning. It is possible that this time was not tracked correctly.
- C. *Flux Specific gravity.* An RMA flux with two specific gravity values was used in a single workstation for different processes. Hence, it was possible that an operator may apply the flux with the wrong specific gravity. This will affect the soldering quality.
- D. *Flux Amount.* The flux application method was manual during the tinning process. This means the amount of flux applied to each component could have varied from operator to operator. Combined with other factors, too much flux may facilitate solder wicking while too little flux may cause dewetting.

The parameter settings for the high and low level of the factors are provided in Table 2. Once the factors were selected, a full factorial experiment with two levels was designed. The levels were identified as high and low to simulate extreme conditions. Inspection was performed following the standard production inspection criteria and the number of PGA leads with solder wicking defect were recorded. The recorded experimental data is shown in Table 3.

5.4. Experiment II

The objective of this experiment was to identify the optimum regions of the presoldering parameter settings of the significant factors. Based on the results of Experiment I, which are discussed in Chapter 6, flux amount and PGA lead surface texture were the two factors considered in Experiment II. As shown in Table 4, a full factorial experiment at two levels was designed to avoid confounding of possible interactions. The

Table 2. Parameter settings for Experiment I

Factors	Levels	
	High (1)	Low (2)
Lead roughness (A)	120 μm (average)	75 μm
Baking Time (B)	20 min.	10 min.
Flux Sp.gr (C)	0.795	0.820
Flux amount/PGA (D)	5 mm^3	2 mm^3

Table 3. Number of defects recorded in Experiment I, as a function of experimental conditions

		A1				A2			
		B1		B2		B1		B2	
	C1	C2	C1	C2	C1	C2	C1	C2	
D1	45	68	48	80	71	60	65	65	
D2	43	75	45	70	100	86	104	96	

two levels were "high" and "low". The amount of flux applied during the experiment was measured with a graduated syringe, based on predetermined high and low values. The lead surface texture or roughness was measured in micro-meters. To simulate worst conditions, PGA leads were intentionally scraped using a manual Etch-Cut tool to induce a high level of surface roughness.

Table 4. Parameter settings for Experiment II.

Factors	Levels	
	High (1)	Low (2)
Flux amount/PGA (A)	5 mm ³	2 mm ³
Lead roughness (B)	120 μm (average)	60μm

After each experimental run all the 462 leads of each PGA were inspected using a reticule microscope and the height of tinning or solder coating up the PGA lead length was measured. Less than 50% of tinning or solder coating height, as measured from the tip of the PGA lead, was considered "Good". As shown in Figure 14, any solder coating above 50% of the PGA lead length was considered "Bad" or defective. The total number of all bad or defective leads were recorded, and are reported in Table 5.

Table 5. Number of defects recorded in Experiment II, as a function of experimental conditions.

	A1	A2	Total
B1	6,8	3,4	21
B2	7,8	9,10	34
Total	29	26	55

Figure 15. Comparison of PGA leads with "Bad" and "Good" tinning. (Solder wicked above 50% of the lead length on the "Bad" lead. Tinning height is less than 50% of the lead length for the lead with "Good" tinning.)

5.5 Experiment III

The multilayer ceramic PCB upon which the PGA is mounted is called a Multi Layer Board (MLB), which is a multilayer ceramic board having dimensions of 13 x 13 x 0.5 inches. The assembly process consists of first mounting and VPS reflow soldering of four layered BGAs called Inter Posers (IP) on the MLB. Second, flux is applied on top of each BGA (IP). Third, a pre-soldered or tinned PGA is mounted on each Inter Poser and fourth, the assembly is VPS reflow soldered to attach the PGAs on to the IPs. The process sequence is shown in Figure 16. A side view of the package assembly is shown in Figure 17. The MLB assembly is unusually large, dense and thick. The vapor phase reflow equipment selected was configured with a 19 ft. conveyor, four preheaters, one topside preheater, condensation reflow chamber and a cool down zone. Closed loop controls were used to ensure that parameter settings were being maintained.

Figure 16. PGA mounting and MLB assembly process flow.

Figure 17. Side view of Multi-layered ceramic board assembly

5.5.1. Factor selection

Based on the theoretical factors discussed in Chapters 3 and 4, process knowledge and the results of Experiment II, the following factors were selected to be considered in the experimental design:

- A. Preheat time
- B. Preheat temperature
- C. Reflow time
- D. Flux amount.

5.5.2. The design of Experiment III

Initially, both Fractional Factorial and Full Factorial Methods were considered for the design of the experiment. The Fractional Factorial Method was dropped from further consideration since it could not be assumed that no interactions existed between the

identified parameters. Two levels, high and low, known to simulate extreme conditions of the production environment, were chosen to be used with the full factorial testing method. However, the resultant 16 treatments (runs) which would be required for the full factorial method could not be accommodated, using a fully populated MLB, due to the high cost of the MLBs and the PGAs. Therefore, to comply with the requirements of the full factorial test, it was decided to slice four MLBs into four quarter-sized test boards which could be run individually.

In order to replace the quarter-sized MLBs with full MLBs, the effect of substitution had to be evaluated. The primary concern was whether or not the topside temperature of the quarter-sized MLBs was equivalent to the topside temperature of the full-sized MLB. This equivalence of top side temperature throughout the preheat region, if present, would demonstrate equivalent thermal properties to the quarter and full sized-MLBs. To evaluate the effect of MLB size reduction on the reflow profile, the following evaluation was undertaken.

5.5.3. Evaluation of Experimental Procedure

A full-sized MLB and two quarter-sized MLBs were utilized to develop thermal profiles of the board. Then two quarter-sized MLBs and a full-sized MLB were each run four times in the vapor phase machine, using the new thermal profile. For each run, a thermocouple was attached to the surface of the MLB, as shown in Figure 18. Temperature readings were recorded at 15 second intervals. The mean recorded temperature of the Full-sized and quarter-sized MLBs is shown in Table 6. Analysis of the temperature readings was done by computing means and variances for each 15 second interval. Based on the recorded data, a two tailed t test was performed to determine if there was a significant difference between the mean temperature readings of the full-sized and quarter-sized

MLBs. With 95% confidence, the experimental data analyses lead to the conclusion that both full and quarter sized MLBs had equal response to the vapor phase environment, and the differences observed during the heating up and cool down patterns of the boards were not statistically significant. Therefore, it was decided to proceed with the full factorial chip mounting and soldering experiment.

Figure 18. Thermocouple sites on MLB

5.5.4. VPS Soldering Experimental Procedure

A total of 64 PGAs, four on each quarter sized-MLB, were manually mounted. The high and low parameter settings for the four factors are shown in Table 7. All of the test boards were subsequently run in the vapor phase machine according to the full factorial matrix design shown in Table 8 and the data for each run was recorded. After each run, the test boards were cleaned using standard procedures. The packaging assembly configuration does not allow inspection of all solder joints once the PGA is mounted and soldered. Only the leads that are located on the outside rows of the PGA can be visually inspected. Therefore, to perform a complete inspection of all solder joints, each PGA had to be individually lifted, using special chip lifting equipment, and the lead inspected using a

reticule microscope. The level of solder rise or wick was measured and any solder rise above 50% of the vertical length of the PGA lead was considered defective.

Table 6. Mean recorded temperature for Quarter-sized and Full-sized MLB in °C.

Data point	Mean Temp. QRT-sized MLB	Mean Temp. Full-Sized MLB
0	25	25
1	50	50
2	98	97
3	130	128
4	128	127
5	130	131
6	223	223
7	222	222
8	221	220
9	219	219
10	218	217
11	215	216
12	213	215
13	180	182
14	175	177
15	160	157
16	150	155
17	130	142
18	125	130
19	126	125
20	100	125
21	98	100
22	90	90
23	85	87
24	80	83

Table 7. Values of parameter settings for Experiment III

Factors	Levels	
	High (1)	Low (2)
Preheat Time(A)	480 sec.	210 sec.
Preheat Temp.(B)	402.1 °C	350 °C
Reflow Time (C)	310 sec.	210 sec.
Flux amount/PGA (D)	5 mm ³	2 mm ³

Table 8. Number of defects recorded in Experiment III, as a function of experimental conditions.

	C1	A1				A2			
		B1		B2		B1		B2	
		C2	C1	C2		C1	C2	C1	C2
D1	28.6	25.6	23.4	27.8	33.5	30.6	27.7	24.9	
D2	31.4	2	23.8	24.9	26.2	27.8	24.2	29.3	

CHAPTER 6

ANALYSES AND RESULTS

6.1. Experiment I

The ANOVA table is presented in Table 9. The analysis is performed by noting the sources of variations in the left-hand column, which are the factors under test in the experiment. The column labeled " F_o " is the results of the traditional Fisher test for significance. The mean sum of squares for error, is used as the denominator of the F test. The column labeled "Sum of Squares" is the pure effect of each factor. Since all multivariate design of experiments assume that error is allocated equally over all the degrees of freedom within the experiment, each significant effect contains an amount of error which must be subtracted out. The error is added to the estimated error and the total variation within the experiment is constant. The complete statistical analysis was identical to the procedure given in Appendix B, which is the procedure for Experiment II.

At the 99% significance level, the results of Experiment I identified flux amount and PGA lead surface roughness as the most significant factors for solder wicking in the tinning or pre-soldering process. The three-factor and four-factor interactions were found to be negligible and were used to provide an estimate of error. The results were consistent with the theoretical findings discussed in Chapter 4. In the presence of flux, a rough component lead surface promotes solder wicking along the direction of the surface groove. If the surface groove on the component lead is along the direction of solder flow, as in the case of the PGA lead, wicking occurs due to capillary action of the groove. Flux promotes this capillary action.

Table 9. Analysis of Variance for Experiment I data.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_o
A	2170.56	1	2170.56	84.88*
B	39.1	1	39.1	1.53
C	30.1	1	30.1	1.17
D	915.56	1	915.56	35.8
AB	1.6	1	1.6	<1
AC	14.6	1	14.6	<1
AD	2405.6	1	2405.6	94.07*
BC	22.56	1	22.56	<1
BD	1.2	1	1.2	<1
CD	5.6	1	5.6	<1
Error	127.84	5	25.57	
Total	5730.94	15		

* Significant at the 1 percent level ($\alpha = 0.01$)

6.2. Experiment II

With 95 % significance, the results of Experiment II identified an average lead surface roughness of 60 μ m and 2mm³/PGA of flux amount as the optimum settings for a pre-soldering or tinning process without solder wicking defects. The ANOVA table is presented in Table 10. The experimental data indicated that there is a strong interaction between flux amount and lead surface texture. On a rough lead surface, solder wicking occurred independently of the amount of flux used (largest sum of squares). Severe wicking occurred when excess flux (5mm³/PGA) was applied on a rough component lead with average roughness of 120 μ m during the tinning process. The complete statistical analysis is shown in Appendix B.

Table 10. Analysis of Variance for Experiment II .

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_o
A	1.125	1	1.125	1.29
B	21.12	1	21.12	24.14*
AB	15.12	1	15.12	17.3*
Error	3.5	4	0.875	
Total	40.87	7		

* Significant at the 5 percent level ($\alpha = 0.5$)

6.3. Experiment III

The ANOVA table for Experiment III is presented in Table 11. The complete statistical analysis was identical to the procedure given in Appendix B, which is the procedure for Experiment II. At the 95% significance level, flux amount, reflow time, pre-heat temperature and pre-heat time were found to have a significant effect on solder wicking. Interactions between preheat and reflow time, and reflow time and flux amount were significant. A three factor interaction between preheat time-reflow time-flux amount, and between preheat temperature-reflow time-flux amount were also found to be significant. In particular, reflow time and flux amount displayed the strongest effect. When the reflow parameters were set at a pre-heat time (A1) of 480 sec., pre-heat temperature (B1) of 402.1°C, reflow time (C2) of 210 sec. and the amount of flux applied per PGA (D2) was 2 mm³, virtually no solder wicking defect was observed. Further the results of this experiment identified the optimum vapor phase reflow parameter settings for the PGA soldering process, without solder wicking defects, to be high preheat time (480 sec.), high preheat temperature (402.1°C), lower reflow time (210 sec.) and minimum flux amount (2 mm³ per PGA).

Table 11. Analysis of Variance for Experiment III data.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_o
A	11.52	1	11.52	4.7*
B	12.01	1	12.01	4.9*
C	39.61	1	39.61	16.1*
D	17.7	1	17.7	7.2*
AB	7.8	1	7.8	3.2
AC	11.28	1	11.28	4.6*
AD	3.92	1	3.92	1.6
BC	3.01	1	3.01	1.2
BD	3.13	1	3.13	1.3
CD	14.05	1	14.05	5.7*
ABC	2.42	1	2.42	<1
ABD	5.95	1	5.95	2.4
ACD	17.7	1	17.7	7.2*
BCD	24.15	1	24.15	9.8*
ABCD	3.92	1	3.92	1.6
Error	39.36	16	2.46	
Total	217.36	31		

* Significant at the 5 percent level ($\alpha = .05$)

The increase in preheat temperature and time decreases the temperature gradient between the component lead and the land prior to reflow. The land or the pad on the board has a relatively higher thermal mass compared to the lead of the PGA. In the preheating zone, where the heat transfer mechanism is mainly conduction, the lead of the PGA is heated faster than the land and the board, due to its small thermal mass and high heat conductivity. Dwelling of the assembly in the preheating zone of the vapor phase provides adequate time for the land to reach close to the temperature of the PGA lead, thereby reducing the temperature differences. This reduction of thermal gradient between the lead and the land greatly reduces the chance of solder wicking during reflow.

Once the assembly is introduced into the reflow zone of the vapor phase, the dwelling time of the assembly in the reflow zone must be minimized to deter wicking

action. Minimizing the amount of flux minimizes the spreading action of the solder, thereby reducing wicking. When the assembly enters the reflow zone, the lead of the PGA is heated faster than the land. The top surface of the solder on the land underneath the PGA lead also starts to melt and wet the lead. Flux promotes the wetting action, the speed of which is a function of the amount of flux available for creating a clean surface. To achieve a good solder joint without solder wicking, the assembly must be removed from the reflow chamber as soon as the land starts wetting the lead. If the assembly is allowed to dwell in the reflow zone longer, the initial solder that wetted the land will continue to spread and wick up the lead where the temperature is higher, because solder spreads in the direction of higher temperature. In the presence of flux the wicking action of the solder up the lead will be faster.

CHAPTER 7

CONCLUSIONS

The present study has shown that the extent of solder wicking is strongly affected by the component lead texture, the temperature difference between the component lead and the substrate pad during soldering, the solderability difference between the component lead and the substrate pad, the solder alloy composition and the amount of flux present in the soldering system.

The near optimum regions of soldering parameter settings for pre-soldering of PGAs, without solder wicking defects, were found to be an average lead roughness of $60\mu\text{m}$ and flux amount of 2 mm^3 per PGA. Further, the optimum regions of soldering parameter settings for vapor phase reflow of PGAs were found to be pre-heat time of 480 sec., pre-heat temperature of 402.1°C , reflow time of 210 sec., and flux amount of 2 mm^3 per PGA.

Both at the tinning and vapor phase reflow soldering processes, consecutive trial runs were performed, using the identified optimum parameter settings to verify and validate experimental results. A total of 5000 PGAs were tinned, mounted and vapor phase reflowed using the new parameters. Virtually no wicking was encountered. Based on the optimum settings identified in Experiment II and III, new process procedures and vapor phase reflow profiles were developed and standardized. To maintain consistency in the application of the right amount of flux, at both pre-soldering and reflow processes, new fluxing equipment was procured, tested, validated and formally integrated into the process.

By utilizing a full factorial designed experimental approach, information not only about solder wicking defects, but also characterizing and optimizing the multi-variable operation of PGA assembly soldering was obtained. This was accomplished without having to resort to new solder alloy formulations or changes in component lead metallurgy.

Recommendations for Further Research

Further research is required to address some of the critical questions investigated in this study. The following research areas are recommended.

- (1) Phase diagrams are important tools to analyze and understand the metallurgy of solder alloys. But the soldering system is made up of many parameters that a phase diagram cannot fully address. One of these parameters is time. For a complete analysis of solder metallurgy and a good understanding of the soldering system, a phase transformation diagram that incorporates time should be developed. The importance of this is further highlighted by the growing need for absolute control of the soldering processes used for interconnecting packages with increasingly smaller pitch size and high lead count.
- (2) As this investigation demonstrated, it is possible to utilize a statistically designed experiment to optimize vapor phase reflow soldering to eliminate solder wicking defects. But an experiment is a statistical inference and as such it cannot adequately explain the internal mechanisms and the actual dynamics of a system. In fact all the factors that contribute to wicking are still not well understood.⁽⁴⁰⁾ To better comprehend the phenomenon of solder wicking, a thorough understanding of the dynamics of condensation soldering heating is necessary. Unfortunately, very little work has been done on this type of transient condensation heating. Finite element

modeling, combined with solder micro-structure analyses, are options that could possibly provide a breakthrough.

- (3) The results of the experimental investigation, and every day observation, indicate that surface roughness affects the static contact angle and enhances the rate of spreading of a liquid/solder on a surface. However, full analytical derivation of Eq.[12] has never been provided. Comprehensive understanding of this phenomenon could also have significant technological impact.

REFERENCES

1. Amdahl Corporation, "Internal Technical Document," Sunnyvale, California, (1992), p. 98.
2. McLellan, N., and Schroen, N., " TI Solves Wicking Problem," Circuits Manufacturing, Vol. 3, No. 9, (1987), pp. 56-62.
3. "Selective Plating for surface-mounted component lead," IBM Technical Disclosure Bulletin, Vol. 29, No. 22, (1986), p. 53.
4. John, F. R., "Vapor Phase Soldering Considerations," Proceedings of the Technical Conference Sixth Annual International Electronics Packaging Conference, November 17-19, (1986), p. 323.
5. Selvaduray, G.S., "Die Bond Materials and Bonding Mechanisms in Microelectronic Packaging," Thin Solid Films, (1987), p. 435.
6. Amdahl Corporation, "Internal Technical Document", Sunnyvale, California, (1992), p. 47.
7. Wassink, R.J., Soldering in Electronics, Electrochemical Publications, (1984), p. 39.
8. Prasad, R.P., Surface Mount Technology Principles And Practice, Van Nostrand Reinhold, (1989), p. 425.
9. Manko, H. H., Solder and Soldering, McGraw-Hill, (1984), p. 76.
10. Hart, C., "Double-sided attach using reflow solder," Circuits Manufacturing, Vol. 5, No. 6, (1987), p. 18.
11. Lau J.H., Solder Joint Reliability, Van Nostrand Reinhold, (1991), p. 110.
12. Stephen W.H., Handbook of Surface Mount Technology, John Wiley and Sons, (1988), p. 176
13. Wassink, R.J., and Gerven, J.A., "Displacement of Components and Solder during Reflow Soldering," Soldering and Surface Mount Technology, Vol. 2, No. 5, (1989), p. 39.
14. Polczynski, M., Seitz, M., and Hirthe, H., "A New Technique for Monitoring Solder Paste Characteristics," Proceedings of the Technical Conference Sixth Annual International Electronics Packaging Conference, November 17-19, (1986), p. 689.
15. Huh, C., and Mason, S.G., "Effect of Surface Roughness on Wetting," Interface Science, 1977. p 31.
16. Kalmbach, J.B., "Vapor phase reflow: an improved process," Electronic Packaging and Production, Vol. 4, No. 6, (1991), p. 22.

17. Wenger, G.M. and Mahajan, R.L., "Condensation soldering technology, Part 1: Condensation soldering fluids and heat transfer," Insulation / Circuits, Vol. 3, No. 8, (1979), p. 133.
18. Holman, J.P., Heat Transfer, McGraw-Hill Publishing Company, (1990), p. 12.
19. Hutchins, C., and King, S., "The surface mount solder reflow process," Printed Circuit Assembly, Vol. 5, No. 10, (1987), p. 68.
20. Linman, D.L., "Vapor phase reflow: an overview," Soldering and Surface Mount Technology, vol. 5, No. 7, (1990), p. 484.
21. Manko, H.H., Soldering Handbook for Printed Circuits and Surface Mounting, Van Nostrand Reinhold, (1986), p. 126.
22. DeVore, J.A., "Solderability," Journal of Metals, Vol. 1, No. 3, (1984), p. 51.
23. Pignato, J., "New phase in vapor phase," Circuits Manufacturing, Vol. 9, No. 4, (1987), p. 45.
24. Wassink, R.J., Soldering in Electronics, Electrochemical Publications, Ayr, Scotland, (1984), p. 90.
25. Flattery, D.K., "Minimizing solder defect rates through the control of reflow parameters," Surface Mount Technology, Vol. 2, No. 11, (1986), p. 33.
26. Manko, H.H., Soldering Handbook for Printed Circuits and Surface Mounting, Van Nostrand Reinhold, (1986), p. 98.
27. Cobb, B.R., "Tailor-made soldering," Circuits Manufacturing, Vol. 3, No. 8, (1988), p. 25.
28. Prasad, R.P., Surface Mount Technology Principles And Practice, Van Nostrand Reinhold, (1989), p. 440.
29. Winter, C. and Seidinger, K.R., "Understanding vapor phase reflow soldering," International Society Hybrid Microelectronics, Vol. 4, No. 3, (1987), p. 185.
30. Spitz, D.M., Cobb, B., Yenawine, D.L., Wolvertson, W.M., "Solderability optimization for vapor phase reflowed, surface mount electronics assemblies," Surface Mount Technology, Vol. 6, No. 8, (1988), p. 53.
31. Ruffing, J.F., "Vapor phase soldering considerations," International Electronics Packaging Society, Vol. 4, No. 8, (1986), p. 51.
32. Prasad, R.P., Surface Mount Technology Principles And Practice, Van Nostrand Reinhold, (1989), p. 430.

33. Wassink, R.J., Soldering in Electronics, Electrochemical Publications, Ayr, Scotland, (1984), p. 48.
34. Walpole, R.E., and Myers, R.H., Probability and Statistics for Engineers and Scientists, Macmillan Publishing Company, (1985), pp. 324-326.
35. Juran, J.M., Quality Control Handbook, Fourth Edition, McGraw-Hill Book Company, (1988), p. 26.3
36. Ross, R.J., Taguchi Techniques for Quality Engineering, McGraw-Hill Book Company, (1988), p. 91.
37. Montgomery, D.C., Design and Analysis of Experiments, Third Edition, John Wiley and Sons, (1991), p. 275.
38. Fujitsu America Corporation, "Internal Technical Document," San Jose, California, (1991), p. 47.
39. Ruffing, J.F., "Vapor Phase Soldering Considerations," Proceedings of the Technical Conference Sixth Annual International Electronics Packaging Conference, November 17-19, (1986), p. 1160.
40. Wassink, R.J., Soldering in Electronics, Electrochemical Publications, Ayr, Scotland, (1984), p. 560.

BIBLIOGRAPHY

- Bhote, K.R., World Class Quality, American Management Association, (1991).
- Boys, C.V., Soap Bubbles, Their Colors and Forces which Mold them, Dover Publications, (1959).
- Coombs, C.F., Printed Circuits Handbook, McGraw-Hill Book Company, (1988).
- Juran, J.M., Quality Control Hand Book, Fourth Edition, McGraw-Hill Book Company, (1984).
- Manko, H.H., Soldering Hand Book for Printed Circuit and Surface Mount, Manko Associates Inc., (1986).
- Ross, P.L., Design of Experiments and Taguchi Methods, McGraw-Hill Book Company, (1988).
- Taguchi, G., Introduction to Quality Engineering, Asian Productivity Organization, American Supplier Institute Inc., (1990).
- Tummala, R.R., and Rymaszewski, E.J., Microelectronics Packaging Handbook, Van Nostrand Reinhold, (1989).
- Walpole, R.E., and Myers, R.H., Probability and Statistics for Engineers and Scientists, Third Edition, Macmillan Publishing Company, (1978).
- Wassink, R.J., Soldering in Electronics, Electrochemical Publications, Ayr, Scotland, (1984).

APPENDIX A

Multilayer Board Assembly (MLB) Production Process

A.1 Board Preparation

BGAs are mounted and reflow soldered on the MLB prior to the mounting of PGAs. In addition wire bonding that require over 50,000 solder joints must be performed before PGA mounting.

A.2 PGA Tinning or Presoldering

The PGAs are prepared concurrently with the board. Each PGA has 462 pins which are gold plated to prevent oxidation during storage. In order to ensure a reliable solder joint, the gold plating must be removed and the leads presoldered before the PGAs are mounted on the board.

Incoming PGAs are inspected visually to ensure that the correct chips are received and that all chips meet specifications. Once visual inspection is completed, the chips are placed in a lead straightening jig and loaded in to an automatic machine that check the straightness of each PGA lead. The PGA lead must be straight to ensure lead planarity during mounting.

Next, PGAs are mounted in a presoldering jig and flux is applied. The PGAs are preheated and the leads dipped in a molten SnPb solder bath. Preheating the packages reduces thermal shock and also activates the flux that cleans the lead surface, to ensure good solder joint formation. Finally, the PGAs are removed from the presoldering jig, carefully cleaned, inspected and routed to the PGA mounting process.

A.3 PGA Mounting Process

PGAs are mounted on the MLB using a pick and place robot with a visual system. The robot applies flux on the BGA, picks the PGA and places it on the BGA which is already mounted and soldered on the MLB. To ensure precise alignment of PGA as it is mounted on the BGA, each PGA package has two guide pins. The guide pins are matched by two guide blocks mounted at opposite corners of the BGA. This ensures that the other 460 leads are carefully aligned with the land or pads of the BGA. After all PGAs are mounted, a pressure jig is placed on the assembly. The pressure jig secures the chip alignment during reflow soldering. Then the assembly is reflowed in an in-line vapor phase reflow machine.

After reflow soldering, the assembly is cleaned and the solder joints are inspected visually. Because of the assembly configuration, only solder joints located on the two outermost rows at each side of the PGA, or 27% of the joints, can be inspected. If defects are found, the PGA is lifted and reflowed, using a single component reflow machine.

APPENDIX B
Experiment II
Presoldering or Tinning process optimization

The Process: The production process sequence is described in Appendix A.

Problem. To eliminate wicking or more than 50% rising of solder up the vertical lead of the PGA during tinning process.

Objective. To identify critical parameters that contribute to solder wicking and to optimize and control the tinning process.

Measurement. Tinning height, **Y** is measured using a vertical reticule microscope. If tinning height is more than 50% of the PGA lead length, then solder has wicked.

Factor Selection and levels

The results of Experiment I, identified two factors that are significant to the presoldering or tinning process. The two factors were PGA lead surface texture or roughness before tinning and flux amount. Other factors such as flux type, tinning machine parameters, and solder bath condition were not considered because their effect on wicking was found to be insignificant in an earlier experiment conducted to characterize the tinning process.⁽³⁸⁾

Flux amount was chosen because flux is applied manually in this process and there is a variation in the amount of flux applied from operator to operator. Understanding the impact of this flux amount variation to solder wicking was considered critical. The surface condition of the PGA lead was considered as another important factor in this experiment because surface condition affects the spreading ability of solder due to capillary effect which potentially means promoting solder wicking. Therefore a two factor two level full factorial experiment was designed.

<u>Effect</u>	<u>Degree of freedom</u>
A = Flux	a - 1
B = Roughness	b - 1
AB interaction	(a-1)(b-1)
Error	ab(n-1)
<hr/>	
Total	abn-1
<hr/>	

Hypotheses Testing

A. We are interested in testing the equality of row treatment effect (μ_r)

$$H_0: \mu_{r1} = \mu_{r2} = 0$$

H_i : at least one μ_{ri} is not = 0

B. And the equality of column treatment effects: (μ_c)

$$H_0: \mu_{c1} = \mu_{c2} = 0$$

H_i : at least one μ_{ci} is not = 0

C. We are also interested in determining whether row and column treatments interact.

$$H_0: (\mu_{rc})_{ij} = 0$$

H_i : at least one $(\mu_{rc})_{ij}$ is not = 0

Critical Region : $F_{.05,1,4,\dots} = 7.71$

Experimental Procedure

Production process parameters were checked and set to the normal production run conditions. In the first experiment trial, two PGAs were randomly picked and sent through the normal tinning process. Except that the flux amount applied prior tinning was minimum than normal. Amount of flux applied to the PGA was controlled by using a graduated syringe. Then the PGAs were cleaned and the tinning length up the PGA lead was measured using a reticule microscope. Any solder rise above 50% of the PGA lead length was recorded as a solder wicking defect. All 462 leads of each PGA was inspected. In the

second trial the flux amount was raised to maximum level. The same procedure was repeated and the data recorded.

On the *third trial* the flux amount was set as in *Trial 1* and instead of using the existing lead straightening jig, a new jig with wider hole diameter was used, because it was thought that the narrow hole diameter of the existing lead straightening jig is scraping the PGA lead creating a rough lead surface. Again the same inspection and data recording was performed after tinning. On the *fourth trial* the flux amount was set as in *Trial 2* and the existing lead straightening jig was used during the lead straightening stage of the process. PGAs were inspected and data was recorded. The data of the experimental runs that was also presented in the text is shown in Table 5.

Table 5. Transformed data for two-way ANOVA

	A1	A2	Total
B1	6,8	3,4	21
B2	7,8	9,10	34
Total	29	26	55

Data analysis and calculations:

$$SS_T = \left(\sum_{i=1}^n y_i^2 \right) - T^2/N$$

$$SS_A = \left[\sum_{i=1}^{Ka} (A_i^2 / n_{A_i}) \right] - T^2/N$$

$$SS_{AXB} = \left[\sum_{i=1}^c ((AXB)_i^2 / n_{AXB}) \right] \dots\dots\dots \text{etc.}$$

$$SS_T = 6^2 + 8^2 + 3^2 + \dots + 10^2 - (55^2/8) \\ = 40.875$$

$$SS_A = 29^2/4 + 26^2/4 - (55^2/8) \\ = 1.125$$

$$SS_{AXB} = 14^2/2 + 7^2/2 + 15^2/2 + 19^2/2 - [55^2/8 - 1.125 - 21.125] \\ = 15.125$$

Degrees of freedom, v

Total *degrees of freedom*,

$$v_T = N - 1 = 8 - 1 = 7$$

Factor A *degrees of freedom*:

$$v_A = K_A - 1 = 2 - 1 = 1$$

Factor B *degrees of freedom*

$$v_B = K_B - 1 = 2 - 1 = 1$$

Interaction (AXB) *degrees of freedom*

$$v_{AXB} = (v_A) (v_B) = 1 \times 1 = 1$$

Error *degrees of freedom*:

$$v_e = v_T - v_A - v_B - v_{AXB} \\ = 7 - 1 - 1 - 1 = 4$$

Analysis

The summary of the ANOVA results indicate that flux amount by itself has no significant effect on solder wicking, surface roughness by itself has a substantial effect (largest SS) on solder wicking, and the interaction of flux and lead surface roughness play a substantial part in promoting solder wicking. The flux amount effect depends on the level of surface roughness of the SMP lead and vice versa. The average of all results under A₁ and all results under A₂ are not very different and the average of all results under B₁ and all results under B₂ are different. This means amount of flux has no significance impact, but

variation in surface condition is significant. The repeated data points at each interaction combination imply there is some error variation around the average for that combination. Note that in this case the conditions A_1B_1 and A_2B_2 do not appear to be different. Over all the experimental results indicate that the effect of surface condition is critical and the combination of surface condition and flux amount is also significant. It is also clear that if the lead surface is rough, wicking will occur regardless of the flux amount applied to the lead.