VARIABLE FREQUENCY MICROWAVE REFLOW OF LEAD-FREE SOLDER PASTE

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Pamela Patrice Reid

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VARIABLE FREQUENCY MICROWAVE REFLOW OF LEAD-FREE SOLDER PASTE

Approved by:

Dr. Paul A. Kohl

Dr. Sue Ann Bidstrup Allen

Dr. Dennis W. Hess

Dr. Gary S. May

Date Approved: 05/24/04

DEDICATION

This thesis is dedicated to the memory of my grandmother, Mrs. Vernelle Mary Johnson Reid. Her love and support meant the world to me.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

As the world moves towards eliminating lead from consumer products, the microelectronics industry has put effort into developing lead-free solder paste. The major drawback of lead-free solder is the problems caused by its high reflow temperature. Variable frequency microwave (VFM) processing has been shown to allow some materials to be processed at lower temperatures. Issues addressed in this study include using VFM to reduce the solder reflow temperature, comparing the heating rate of different size solder particles, and comparing the reliability of VFM reflowed solder versus conventionally reflowed solder. Results comparing the effect of particle size on the heating rate of solder showed that the differences were negligible. This is due in part to the particle sizes overlapping. Many lead-free solder pastes reflow around 250°C. Results indicate that when using the VFM, lead-free solder paste will reflow at 220°C. The reliability of solder that was reflowed using the VFM at the reduced temperature was found to be comparable to solder reflowed in a conventional manner. Based on these findings, VFM processing can eliminate the major obstacles to making lead-free solder paste a more attractive option for use in the microelectronics industry.

CHAPTER 1

INTRODUCTION

Today's society is moving away from lead-based materials due to their toxicity. When released into the atmosphere, lead has been found to cause kidney, brain, and central nervous system damage in humans. American human lead concentration has increased 500 fold since the days of prehistoric man. [1] Danger from lead not only affects humans, but also the environment. [2] A large amount of contamination is from electronic waste in landfills. An example of this is when ground water is contaminated by lead leeching from landfills. [3] Exposure also occurs to electronics industry workers who are exposed to lead containing products. Batteries are one source of lead. Lead is also used in a number of microelectronics applications. They include solder paste, printed wiring board finishes, component treatments, and component attachments on printed wiring boards. Due to the large amount of possible lead contamination, the microelectronics industry is moving towards no lead.

The European Union through a proposal known as the Waste for Electronic and Electrical Equipment (WEEE) has set January 2008 as the date for electronics to become lead free. The European Union also approved proposal known as the Reduction on Hazardous Substances (RoHS), which sets July1, 2006 as the date that targeted hazardous materials may no longer be used. There are some exemptions permitted. [4] The Japanese Ministry of International Trade and Industry has set 2005 as the date for the use of lead to be reduced by two-thirds. The Japan Institute for Electronic Packaging calls for the total elimination of lead based solders between 2010-2015. In an effort to compete in the global market, the United States is also trying to eliminate lead from products produced here also. In January 2001, the Environmental Protection Agency (EPA) proposed legislation to decrease the reporting thresholds of lead. There has also been an effort to reduce waste electronic material in landfills. The National Electronics Manufacturing Initiative (NEMI) hopes to completely eliminate lead from electronics products by 2004. [5, 1, 6]

Lead based solder paste was heavily used by the electronics industry due to its desirable properties, which are conducive to the soldering process. The properties include high fatigue resistance, good joint reliability, low melting point, and good wettability. Other properties include low cost and readily available. [1, 7, 8, 6] Traditional eutectic solder is a tin-lead (63%Sn/37%Pb) alloy. A number of alternatives to lead based solder paste have been developed. Some of these lead-free solders include indium, silver, gold, or bismuth alloyed with tin. [9] The industry needs lead-free solder to have comparable or improved reliability over traditional lead based solder. NEMI has determined that tin/silver/copper (Sn/Ag/Cu) are the best alternative to Sn-Pb solder based on its characteristics and comparable reliability to Sn-Pb solder. The Sn/Ag/Cu is the benchmark for all testing involving lead-free solder. [8, 5, 6,10] According to research done by Kehoe et al, lead-free solder based on Sn/Ag/Cu had higher thermal conductivities than SnPb37 alloy. [3] This is important because in addition to providing an electrical and mechanical connection, solder also serves to help dissipate heat. [9] The traditional way to reflow solder for good solderability is in a convection oven where paste is melted, evenly wets the base metal, and then cools to form a joint. [11, 12]

However lead free solders are not without drawbacks. Lead-free solders are more costly than Sn-Pb solders. One of the major issues with lead-free solders is that the curing temperature tends to be higher than that of traditional Sn-Pb solder. A good melting temperature was one of the traits that made lead so popular in the industry. Eutectic tin-lead solders melt around 183°C, while the melting temperature of the majority of alternative lead-free solders is over 200°C. Processing temperatures tend to be 15° to 45° above the solder melting point. Devices can be damaged or compromised when held at high temperatures for long periods of time. High temperatures can result in delamination, crack formation, and low thermal fatigue in solder joints. [13] Substrate warpage can also occur at higher temperatures. [14] Some effort must be made to combat the high curing temperatures of no-lead solder. A way to counteract these high temperatures is to use microwave technology. Microwave technology has been looked at to improve the processing of materials in addition to having several economic advantages to traditional furnace processing. [15]

Organization of Thesis

The purpose of this study is to determine how variable frequency microwave can affect or improve the reflow of lead-free solder. This thesis is divided into 4 chapters. A review of the literature is provided in Chapter 2. Also included in this chapter is information on the materials used and an explanation of the experimental procedures. Chapter 3 is devoted to the results and discussion of the experiments performed. Chapter 4 summarizes the conclusions reached and recommendations for future research.

CHAPTER 2

BACKGROUND

2.1 Literature Review

Microwave processing has been investigated to improve some of the physical properties of the materials processed. A major advantage of microwave processing is that less energy and time is required during processing. There is also a possibility that new materials will be able to be processed and created through microwave technology. Microwave technology is also considered to be environmentally friendly. Reduced processing time and energy used is due to the rapid volumetric heating caused by microwave irradiation. The material heats quickly through rapid dipole reorientation. [15, 16, 17] Previously, most microwave processing was done with fixed frequency microwave sources. Fixed frequency microwave sources are generated through the use of a magnetron. [18] Characteristics of microwave processing are the ability to control the distribution of the electric field, rapid and selective heating, and penetrating radiation. [19,20] These cannot be accomplished with convection heating.

The microwave frequency range is between 300 MHz and 300 GHz. [15] Industrial microwave applications occur at 915 MHz, 2.45 GHz, 5.8 GHz, and 24.124 GHz held at fixed frequencies, with 2.45 GHz being the most common. Microwaves move at the velocity of light. Microwave processing can also reduce the chance of degradation that may occur with conventional heating methods. Microwave energy is absorbed by the material, allowing for the simultaneous heating, as opposed to the convectional thermal heating mechanism, which heats from the outside in. [16] A schematic of the microwave process can be seen in Figure 2-1.

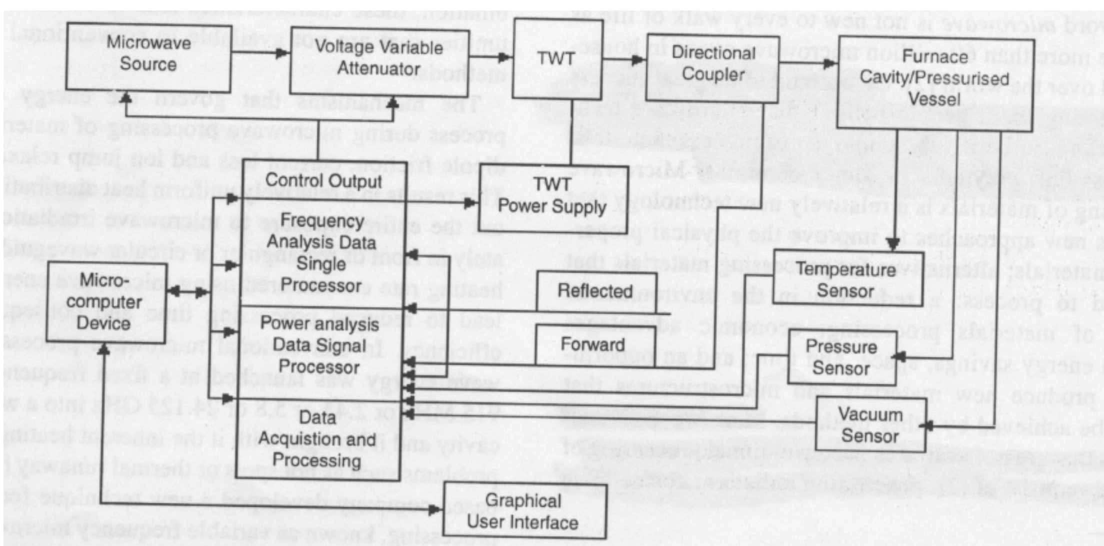

Figure 2-1 Schematic of the microwave process. [20]

The variable frequency microwave (VFM) source is thought to be superior to fixed frequency microwave sources for a variety of reasons. VFM sweeps along a given bandwidth around a central frequency. Microwave heating can result in uniform heat distribution throughout the material, however, this does not always occur with fixed frequency microwave sources. Hot spots are created by areas of the material with higher electric field strength caused by the microwave energy. [20] VFM can help to eliminate heating non-uniformity. The microwaves in a VFM are generated through the use of traveling wave tubes. [18] Based on research completed by Ku et al., when compared to single frequency microwave processing, VFM processing cut the power input and processing time in half. Coupling efficiency can be maximized through the use of VFM. [15] VFM has been successful in several microelectronic processes including bonding, curing, and cross-linking materials, processing underfills, polymerization and sintering ceramics. Although VFM has been successful with many materials, it is not always a suitable processing method. [15,19,18] In order for a material to be processed via microwave technology, microwaves must first be able to penetrate the material, and then the material must be able to convert that electromagnetic energy to heat. This absorbance is related to the dielectric loss, ε''. The loss tangent, is defined as:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}, \quad \textbf{Equation 2-1}$$

where ε' is the permitivity. [15,19,1] Materials with low dielectric loss are difficult to heat though microwave processing due to limited capability for incident power adsorption. Reflections are caused by mismatches in impedance. The relationship between energy absorbed and energy reflected is shown in the following equation:

$$R+A+T=1, \qquad \textbf{Equation 2-2}$$

where R is the fraction of energy that is reflected, A is the fraction absorbed, and T is the fraction transmitted. All portions of this equation are function of the thickness of the medium. [21,22]

Energy transfer is maximized when reflection is minimized. [1] Microwave power absorption can be defined as:

$$P = \frac{1}{2\varepsilon_0 \varepsilon'} * \tan\delta * E^2, \qquad \textbf{Equation 2-3}$$

where ε_0 is dielectric permitivity of free space and E is the electric field strength. [17]

The dielectric constant is a determining factor as to how much energy is reflected from the surface of the sample and how much is absorbed. [15] Some materials are difficult to heat due to others factors that include high conductivity and loss factors. Materials with high ionic or metallic conductivity can be difficult to heat through microwave energy. All these play a factor in how much microwave energy is absorbed by the solder paste. At microwave frequencies, highly polar materials tend to have high dielectric loss. [1] A high dielectric loss can cause rapid bulk heating which leads to the decrease in processing time of a material.

According to Tummala [1,pg. 529], skin depth is "the distance from the metal surface, beyond which the current density falls below 1/*e* (about 37%) of its original magnitude." Skin depth (δ) can be mathematically expressed as:

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}}, \qquad \textbf{Equation 2-4}$$

where μ_0, is permeability; σ is specific electrical conductivity, and ω is microwave frequency. [21] Absorption of microwaves varies with conductivity. [23] Since the skin depth is a function of conductivity, absorption is also related to the skin depth. The lower the conductivity, the greater the absorbed power on the surface. In theory, if power is absorbed on the surface of a material, the smaller the surface area, the greater the power absorbed. Therefore, material made up of smaller particles should absorb more power than the same material made up of larger particles. When the thickness of the substrate is much greater than the skin depth, the microwaves are fully reflected from the material. Figure 2-2 shows the skin depth of some common metals. At the frequency used in this research, lead-free solder has a skin depth of about 1 μm.

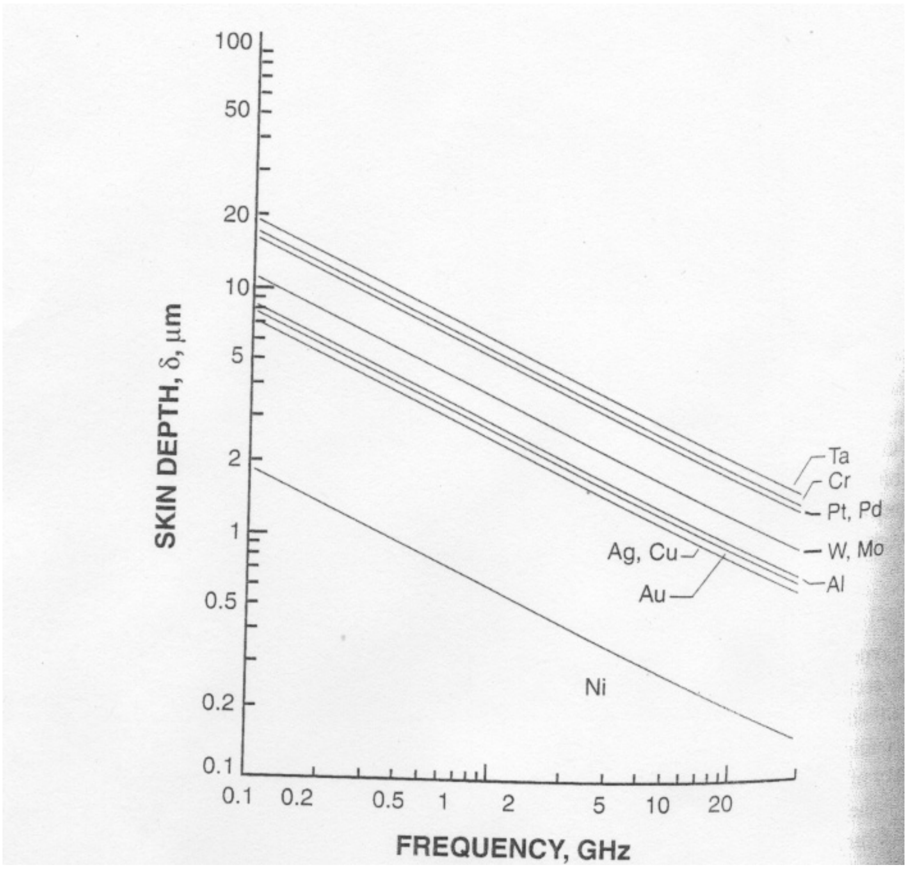

Figure 2-2 Skin depths of common metals as a function of frequency. [1]

A constant ramp rate in the VFM can be difficult to achieve because of the changing absorptivity with state of cure. This may have an effect on the reflow profile and the amount of time necessary for reflow to occur.

According to the Roadmap of Lead-Free Assembly in North America developed by NEMI, solder manufactures have decided on 232°C as the minimum reflow temperature for Sn/Ag/Cu solder. [6] This is an area where VFM processing could also positively impact solder processing. If solder can be cured using the VFM with the substrate at a lower temperature and still have comparable reliability to traditionally cured solder, this could eliminate one of the drawbacks to using lead-free solder. High thermal conductivity assists with heat dissipation. [24] Tests done by Kehoe et al. have shown that the thermal conductivity of Sn-Pb solder is less than lead-free solder including Sn/Ag/Cu. [3] This will help alleviate some of the problems caused by the higher reflow temperature. Due to the higher temperatures necessary for processing lead-free solder, it is imperative that they are processed in an oxygen-freed atmosphere to avoid oxidation. A nitrogen purge will greatly reduce these occurrences. [25] The solderability of lead-free solder is improved and the processing temperature is reduced in a nitrogen-purged atmosphere. [6]

Another problem caused by high temperature processing is the vaporization of water present in electronic packages. This can increase the stress present in solder joints and lead to cracking and fatigue. [13] This will make it extremely important to be able to reflow at lower temperatures in order to not further compromise the reliability of the solder joints.

A second area of stress caused by the increased reflow temperatures deals with the coefficient of thermal expansion (CTE), which causes different materials to expand at different rates when heated. CTE leads to shear strain. [9] The increase in temperature increases the average separation distance between atoms. The coefficient of thermal expansion, α, is described by the following equation:

$$\alpha = \frac{dL}{LdT}, \qquad \textbf{Equation 2-5}$$

where L is the dimension of the material in a given direction and T is the temperature. CTE is measured in parts per million per degree Celsius (ppm/°C). [26] High thermal stress can cause shear deformation of solder balls. [27] Tests have shown that the mechanical properties and reliability of lead-free solders are improved over traditional Sn-Pb solder. [28] Typically, stresses and strains due to CTE and cyclic thermal testing will take place in the solder. This occurs because it is softer than the materials it joins together. [29]

Research conducted by Lu et al., gave the shear strength of Sn/Ag/Cu solder as slightly less than traditional Sn-Pb solder. [30] Shear stress is defined by the following equation:

$$\tau = \frac{P_s}{A_s}, \qquad \textbf{Equation 2-6}$$

where P_s is the load exerted on the sample and A_s is the area of the sample parallel to the applied load. The shear strain is defined as:

$$\gamma = \tan\alpha = \frac{\Delta y}{z_0}, \qquad \textbf{Equation 2-7}$$

where Δy is the distance the sample is moved by the load in the y direction and z_0 is the length of the area where the load is applied. [26] Shear strain of the solder can also be determined through use of the CTEs of the materials used. The formula is defined as:

$$\gamma = \frac{L}{h}(\alpha_b - \alpha_c)(T_{\max} - T_{\min}), \quad \textbf{Equation 2-8}$$

where L is the distance of the solder joint from the neutral point, α_b is the CTE of the board, α_c is the CTE of the component, T_{max} is the maximum temperature the assembly is heated to, and T_{min} is the temperature the assembly is cooled to. [1]

Once the shear stress and shear strain have been determined, the shear modulus can then be calculated. Shear modulus, G, is defined as:

$$G = \frac{\tau}{\gamma}. \qquad \textbf{Equation 2-9}$$

The shear modulus for some lead-free solders have been calculated.

2.2 Materials and Methodology

2.2.1 Materials

The solder paste used in this research is NC-SMQ 230 Pb-Free Solder Paste produced by Indium Corporation of America. As previously mentioned, Sn/Ag/Cu solder is the recommended solder alloy to replace traditional Sn/Pb solder. The formulation used in this work is a 95.5Sn/3.8Ag/0.7Cu alloy. Two different particle sizes of the NC-SMQ 230 Pb-Free Solder Paste were used. The first solder is the Type 3 formulation with particles between 25-45 μm and an 89.3% metal loading. The second solder is the Type 4 formulation with a metal loading of 88%. The size of the particles is between 20-38 μm.

The melting point of the alloy is 217°C. The acceptable peak temperatures range recommended by the manufacturer is 229° and 250°C. The ramp rate should be no more than 1° -2°C per second. Also per Indium's recommendation, the solder should only remain at that temperature for 30-90 seconds to prevent a reduction in reliability. [31] This recipe coincides with the IPC Roadmap's lead free solder profiles. [6] The Indium profile is shown in Figure 2-3.

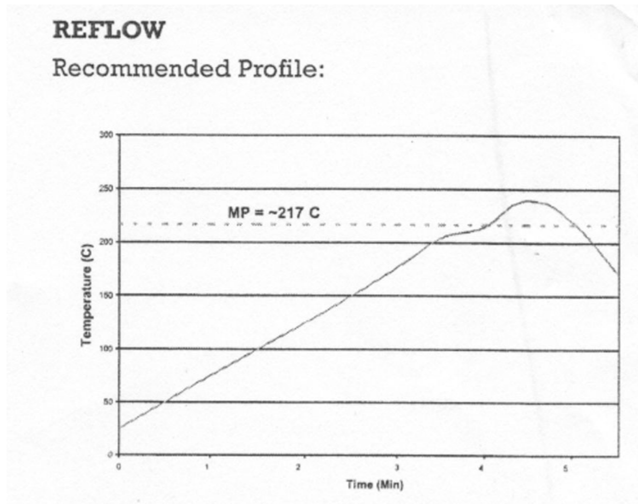

Figure 2-3 Indium Corporation's recommended solder reflow profile [31]

It is preferable that the temperature should not stay within the 100°C to 150°C (preheat setting) for more than 100 seconds to prevent excessive oxidation. The temperature should be maintained over the melting point for at least 30 seconds to avoid poor wetting and inadequate inter-metallic formation. [32] The substrate used is a copper clad bismaleimide triazine (BT) board. The degradation temperature of the BT board is 250°C. This should reduce the substrate warpage problem during reflow.

2.2.2 Methodology

The methodology for the experiments in this research is shown in the following sections. All procedures were followed unless otherwise noted.

2.2.2.1 Preparation of Samples

The procedure for preparing a sample is as follows:

1. Screen print plate resist onto a cooper clad BT board.
2. Soft bake print resist at 90°C for 20 minutes.
3. Etch away the copper.
4. Strip the plate resist leaving copper pads.
5. Screen print solder paste onto copper pads.
6. Reflow solder paste.

A schematic of this procedure can be found in Figure 2-4. Copper was the desired material for the pads the solder was printed on due to the fact that it is the material used the most for pads in PWBs. [9] The plating resist used was Enthone PR3011. It's purpose is to prevent bridging from occurring. The solution used to etched away the copper is a 1:1:10 solution of sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), and water (H_2O). The solution used to strip the plating resist is a sodium hydroxide (NaOH) based developer solution. The pattern screen printed onto the substrate consists of 300 µm circles that are 30 µm tall and 800 µm apart. Each set of solder paste (Sn-Pb, Sn/Ag/Cu

Type 3, and Sn/Ag/Cu Type 4) will be cured via either convection reflow oven or variable frequency microwave. All reflow processes were performed in a nitrogen atmosphere.

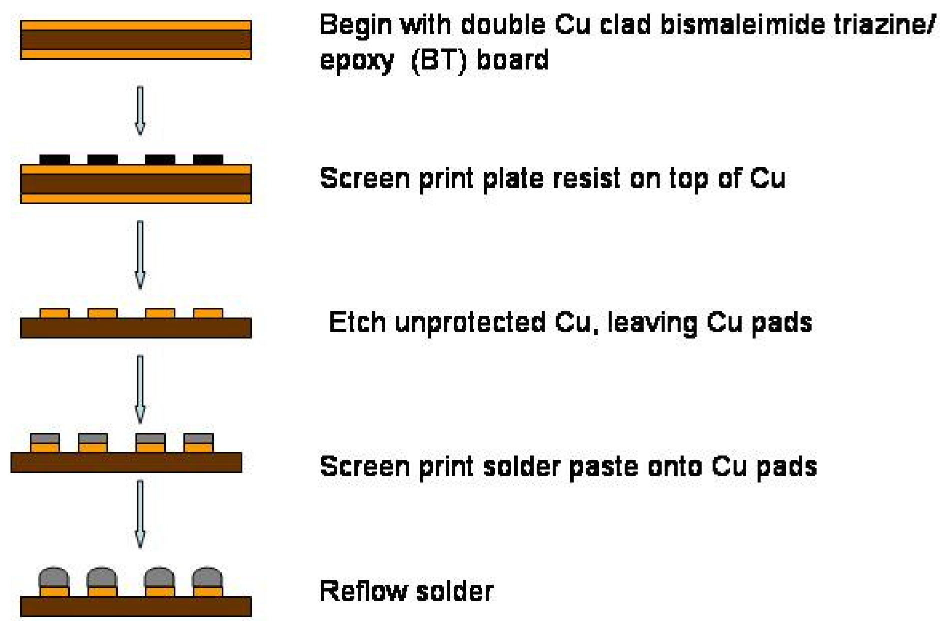

Figure 2-4-Schematic of procedure for preparing samples

In this research the MicroCure 2100 Variable Frequency Microwave Furnace from Lambda Technologies Inc. was used. The VFM is shown in Figure 2-5. The frequency used was 6.4250 GHz with the sweeping occurring at a bandwidth of 1.1500

GHz. All samples in the microwave are placed on a quartz plate before processing. A quartz plate is used due to the fact that it is transparent to microwave energy. The temperature was calibrated prior to the first use. A sample identical to the samples processed in this study was heated inside the microwave using a heated disc. The pyrometer readings were compared to the readings of a surface thermocouple to determine the emissivity necessary and the temperature difference between the VFM's pyrometer readings and the thermocouple readings. Samples cured in the furnace were processed in a Lindburg furnace using the recommended profile.

Figure 2-5 MicroCure 2100 Variable Frequency Microwave furnace used in research.

2.2.2.2 Heating Rate

It has been shown in other work that the particle size of a material can have an effect on the rate at which that material heats. Two formulations of lead-free solder paste, Type 3 and Type 4 were heated under identical conditions to compare their heating rates. The rate at which the solder heats may also be affected by the substrate. Most of the samples used throughout this research are printed onto a stripped BT board with copper patterned on the top. The heating rate of these substrates will be compared with the heating rate of BT boards with the bottom copper layer left intact. The temperature will be measured in the center of the sample with a pyrometer. A contact thermocouple will be used to calibrate the pyrometer. The exact temperature of the solder is not being measured. The temperature measured is actually a combination of the board temperature and the solder temperature. The procedure for comparing heating rates is as follows:

1. Place sample in the VFM.
2. Heat at a constant power of 500W to 230°C.
3. Graph the temperature versus the time elapsed to reach the maximum temperature.
4. Compare heating rates of different particle size solder (or different substrates).

2.2.2.3 VFM Reflow Temperature

VFM processing has been shown to reduce the curing or processing temperature for materials. According to the manufacturer, in order for reflow to occur in a furnace, the solder temperature must reach 229°C. Therefore 230°C will serve as the upper limit for this test. Melting occurs around 217°C, so this will be the lower limit temperature for testing. The following is the procedure for determining the lowest processing temperature for the solder paste:

1. Sample is heated at a rate of 20°C/minute to a maximum temperature of 230°C.
2. Once the temperature is reached, the sample is held at that temperature for 60 seconds.
3. The sample is checked to determine if reflow occurs.
4. If reflow occurs, then Steps 1-3 are repeated, lowering the maximum temperature by 2°C.

The lowest temperature reached will be considered the VFM reflow temperature.

2.2.2.4 Shear Stress

High reliability is important for solder paste. It must be as reliable or more reliable than reflowing the solder in a furnace. One factor in reliability is the shear stress of the solder. This will be done in two ways: the shear stress of the solder as it is attached to the substrate and the shear stress as the solder attaches a silicon die to the substrate. Measurements are obtained using an Instron 5800. The procedure to determine the shear stress of the solder that is attached to the substrate is as follows:

1. Load sample onto the Instron.

2. Measure the load necessary to shear the solder ball from the substrate.

3. Calculate the shear stress by using Equation 2-6.

The procedure for determining the shear stress of the solder as it joins the substrate and the silicon die is:

1. Load sample onto the Instron.

2. Measure the load necessary to shear the solder ball from the substrate.

3. Calculate the shear stress by using Equation 2-6.

The results for solder reflowed by use of the furnace and solder reflowed through use of the VFM were compared.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Heating Rate Results and Discussion

The heating rate of Type 3 and Type 4 solder pastes was investigated using of VFM. The samples were heated at a constant power of 500W to a maximum temperature of 230°C. The purpose of this experiment was to reflow solder paste with VFM and determine if particle size has an effect on the heating rate of the solder paste. The particles in Type 3 solder paste have a diameter between 25-45 μm. The particles in Type 4 solder paste have a diameter between 20-38 μm. The patterns using the two types of particles were printed in an identical manner and processed under identical conditions. When heating, many of the samples did not reach 230°C. Table 1 shows the maximum temperatures reached by several samples. The minimum amount of time taken for the samples to reach their maximum temperatures is also shown. The samples selected for use in the table were the samples with the most consistent heating rates available. The amount of time they were allowed to heat is also shown. Heating was stopped when samples appeared to no longer have a real increase in temperature. The time necessary to heat the samples is too long for most practical applications. Under normal circumstances, samples would be ramped to their desired temperature in a radiant or convection oven. None of the samples reached the target temperature of 230°C. This may be due in part to the fact that the samples are being heated at a constant power instead of a constant ramp rate. The samples come to steady state at a particular temperature at around 500 Watts. This problem may be alleviated when they are heated at a constant ramp rate as opposed to being heated at a constant power. This was tried in later experiments. This will force the temperature to increase steadily instead of it increasing due to the amount of power being applied. Another option might be to use a higher power VFM. This would allow more power to be applied, thus causing the temperature to increase at a faster rate. Since the maximum VFM power for this particular instrument is already being applied, the temperature may not be able to be increased. As shown in the table, the heating rates for the samples varied widely. Only the pattern of the curve was consistent. However, there is no obvious difference in any of the samples. It is unclear why the heating rates differ so much between the same solder paste types.

Table 1- Heating rate comparison from selected samples

Solder Paste Type	Maximum Temperature (°C)	Time To Maximum Temperature (minutes)	Total Heating Time (minutes)
3	229	69.3	69.6
3	223	102.5	103.6
3	223	104.7	113.1
3	206	32.8	34.0
4	225	21.6	21.7
4	222	86.4	93.4
4	206	32.5	23.5

All samples were processed under identical conditions.

Figure 3-1 shows the typical heating rate of Type 3 solder paste. The samples used ion Figure 3-1 are the same samples from the Table 1. The typical heating rate of Type 4 is shown in Figure 3-2. To compare the heating rates of Type 3 and Type 4, their averages were graphed together. This comparison can be seen in Figure 3-3. The curves almost completely overlap each other. Error analysis was completed using the standard deviation and a confidence factor of 95% for each individual point in the averages. The standard deviation was determined by using Equation 3-1.

$$std\ dev = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}, \qquad \textbf{Equation 3-1}$$

where n is the number of points. After completing error analysis, the difference between the heating rates was negligible. When the individual Type 3 and Type 4 curves that were used to determine the averages were added, most fall within the error bars, however, not all. Due to the large number of points, only an few error bars are shown in the figures. All of the curves start out with the same slope. After about 200°C, the heating rate begins to change. At higher temperature, both Type 3 and 4 seem to heat more slowly. Although some deviation occurs, with respect to the error bars, the heating rate only varies slightly. This is more likely due to the fact that the size distribution of smaller diameter particles in the Type 3 solder paste overlaps with the larger diameter size particles of the Type 4 solder paste. The particles are randomly distributed in the solder paste. It is impossible to know what the particle size of each cross-section of solder. It is highly possible that some solder balls of Type 3 and Type 4 could have exactly the same size particles present. The reflow rates of Type 3 and Type 4 were visually compared on silicon wafers. The solder was screen printed onto the wafers. The wafers were then placed on a hotplate and allowed to heat up to 230°C. Based on visual observations, Type 4 began melting slightly before Type 3. Type 4 began reflowing at 114°C, while Type 3 started melting at 117°C. This difference is assumed to be negligible based on the results of heating rates of the solder paste when heated in the VFM.

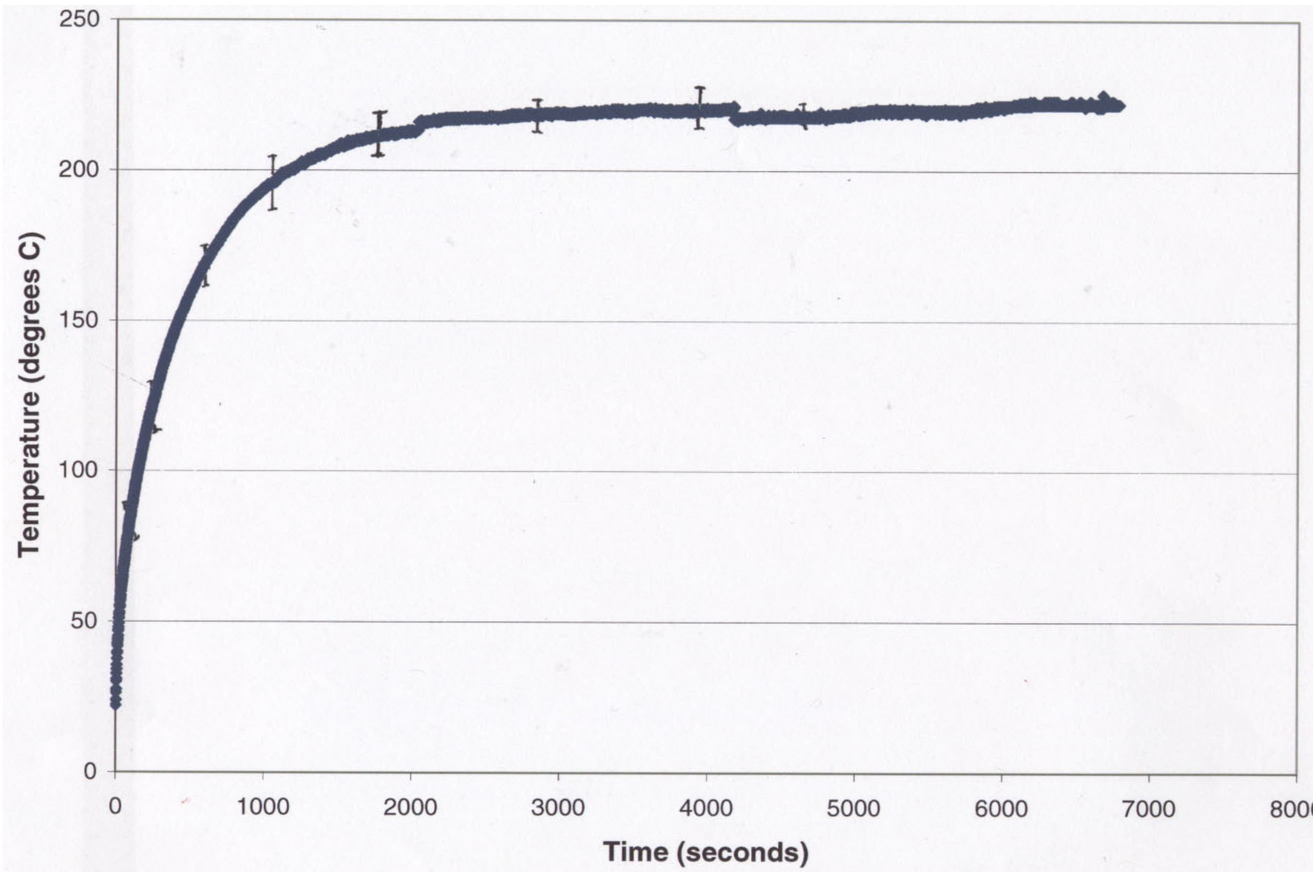

Figure 3-1- Typical heating rate for Type 3 solder paste.

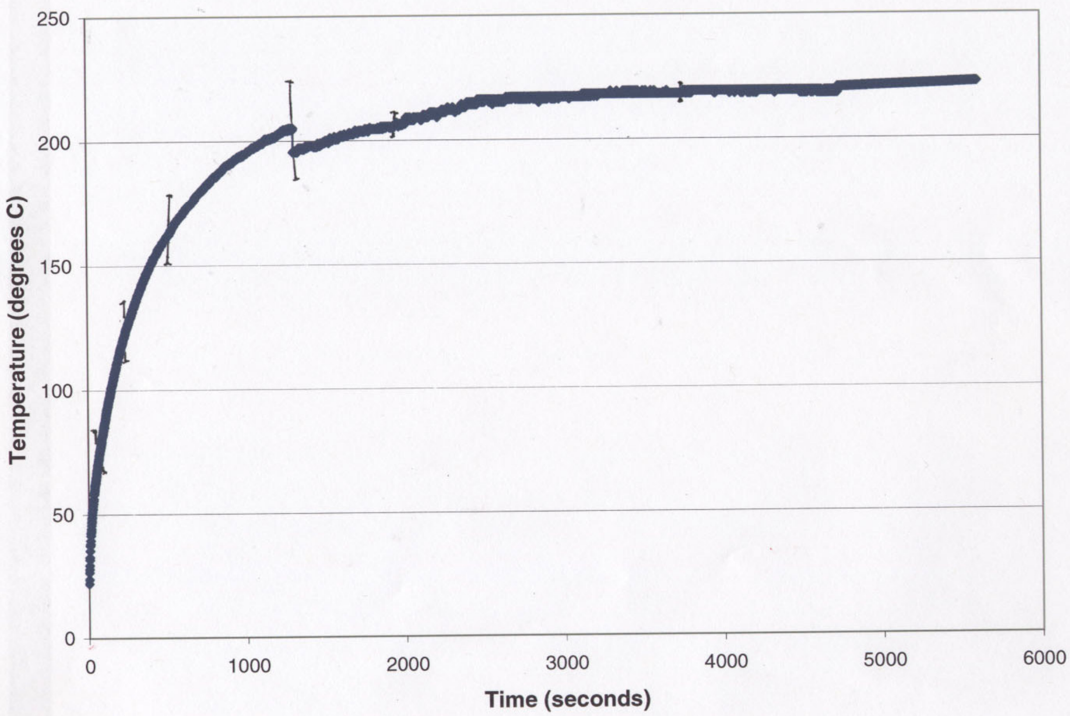

Figure 3-2- Typical heating rate for Type 4 solder paste

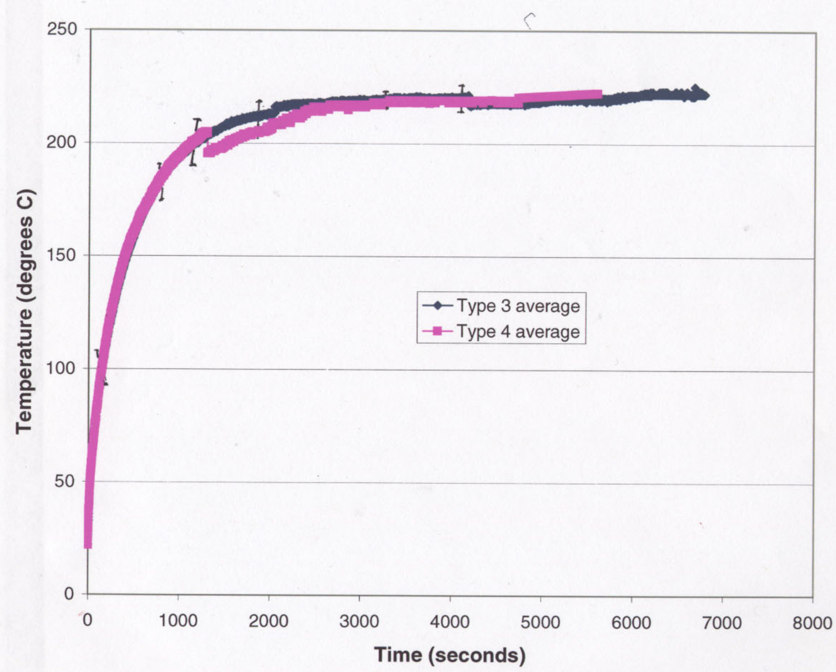

Figure 3-3- Comparison of typical heating rates for Type 3 and Type 4 solder paste.

Another note of interest in the heating profiles is the shape of the curves. All samples began heating rapidly, slowed, and then leveled off before reaching the maximum temperature. This corresponds to information found in the literature. The absorptivity changes as the cure progresses. This occurs due to the fact that as the paste melts, the particles are no longer able to absorb energy as well. [18] This is due in part to the fact that more energy is absorbed during the melting process. Thus, the heating rate begins to level off. The temperature of both Type 3 and Type 4 solder paste remained constant for extremely long periods of time. Table 2 shows the initial point at which the temperature began to level for some of the samples from Table 1. The samples selected took the longest to reach their maximum temperature. In all of these examples, the temperature began to level off near the melting point of the solder paste, which is 217°C. A possible explanation for this is that the energy absorbed was used to create the phase change. The energy required for melting to occur caused the temperature to increase at a very slow rate.

Table 2-Temperature of stagnation for selected samples.

Solder Type	Initial Point of Constant Temperature (°C)	Time at which Temperature Became Constant (minutes)	Maximum Temperature Reached (°C)	Maximum Time (minutes)
3	219	27.7	229	69.6
3	215	35.6	223	103.6
3	215	44.2	222	113.1
4	215	40.4	220	93.4

Previous work has shown that smaller particle size can increase the heating rate of some materials. However, as the particle sizes continue to decrease, this effect no longer occurs. [33] The major advantage the smaller particle size would have is that if it heats faster, then the length of time components are exposed to high temperatures is decreased. This is an important factor in the degradation of an electronic package. However, there is no evidence based on the data in this study that the particle size of the solder affected the heating rate.

Based on the average heating rates of the solder paste, a ramp rate was established to compare the way solder reflowed in the VFM compared to a conventional furnace. At a comparable ramp rate in the furnace, less than one-fourth of the solder reflowed. VFM processing allowed total reflow to occur. There are several reasons why the reflow occurred faster during VFM processing compared to furnace heating. In this research, the frequency was 6.425 GHz, corresponding to a wavelength of ~0.0467 cm. This is much larger than the skin depth, so the solder absorbs the microwaves. Also, the microwaves can penetrate deep into the solder. Therefore, the microwaves are readily absorbed and converted to heat, thus allowing for better heating of the solder through VFM processing as opposed to furnace reflow.

In studies done by Alekseev and Ziskin with millimeter waves and thin water samples, for samples with a thickness of less than 0.3 mm, the smaller the thickness, the better the absorption of the radiation. [22] Microwaves behave in a similar manner. Since the solder is 0.03 mm thick, the solder should have very good absorption via VFM processing. Based on research done by Ku et al. using the MicroCure 2100, the reflectance was lowest (under 35%) in the 6.5-8 GHz range. [20] Due to the sweeping of the frequency in VFM processing, the frequency used in this study falls within that range. If, indeed the reflectance is low in this case, it supports the concept that the energy reflected is low, which leads to higher absorption of microwaves by the solder paste.

The rate of heating of solder paste on different BT boards was also compared. All of the previous samples have had the copper surface stripped off the back of the board. The copper pattern is 300 μm diameter circles with 800 μm spaces between them. They will be compared to samples with copper on the bottom surface. The bottom of the board had a full surface copper finish along with the 300 μm copper circle pattern on top. This will be referred to as the "single sided Cu". The boards were heated in the same fashion as used for the various particle size samples in order to compare the heating rates. Type 3 solder paste was used in the studies. The graph showing the comparison is presented in Figure 3-4.

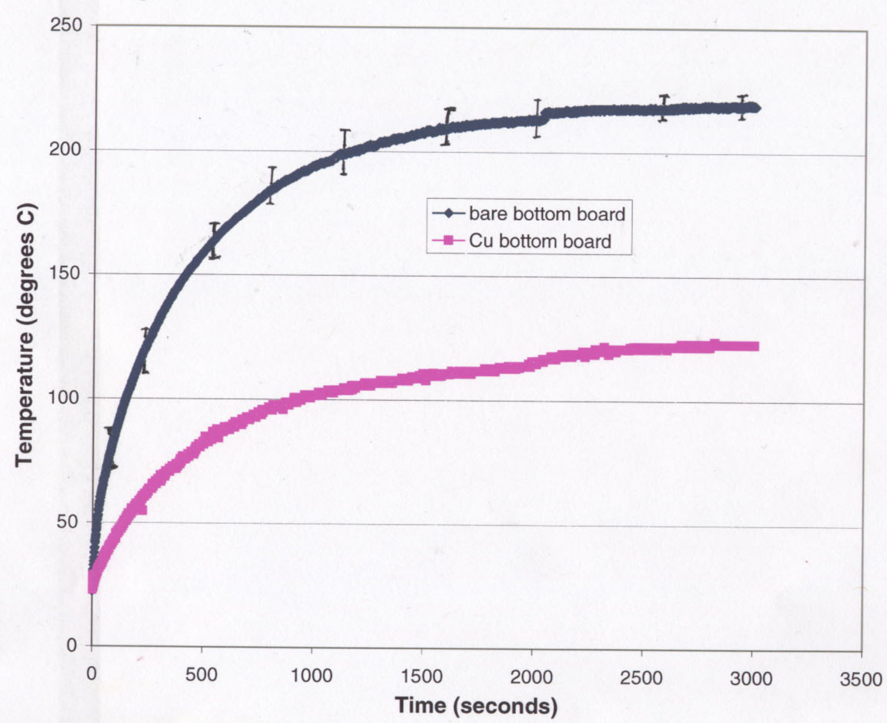

Figure 3-4- Comparison of heating rate of bare and single sided copper (Cu) BT boards

The shape of the temperature vs. time curves for the samples with and without copper on the bottom surfaces did not correlate in the same manner as the samples that were processed with the same bottom surface. The sample without copper on the bottom surface begins to heat quickly and then the temperature levels off. The single sided Cu board initially heats more slowly before coming to a more constant temperature. The initial slope of the curve is lower compared to that of the bare bottom board. After 50 minutes, the temperature of the single sided Cu board had only reached 122°C. Based on the pyrometer readings, it heated up much slower than the bare BT board. However some of the solder on the edge of the board reflowed and the board started degrading in that area, indicating that the edge was heating up faster than the center of the bare board. The overall heating rate in the center of the board was slower, however. Previously, the board without copper on the back reached at least 200°C in the same amount of time. The temperature does not begin to level off until after that point.

These findings correlate with previous research conducted by Sung. [34] In that work, Sung compared BT boards that were completely bare with samples that had 20 µm thick copper surfaces on both sides, the top surface, and the bottom surface. The double copper clad samples heated quickly followed by the heating rate of a BT board with a copper top surface, and the bare BT board. BT boards with a full copper surface on the bottom heated significantly slower than any other boards and the maximum temperature reached was also significantly lower. [34] The large amount of copper on the back of the board was reflecting the microwaves. Alternatively, the copper could have acted as a heat sink. However, the temperature effect does not correlate with the mass of the copper. Reflection of the microwaves would reduce the electric field present in the board and block the microwaves from being absorbed by the board and the solder paste. [34]

Solder is used to surface mount components. Solder paste was screen printed onto the BT boards in the same manner as the previous samples. Silicon die (2.5 mm x 2.5 mm) were placed on top of the solder paste using tweezers. The samples with the silicon die were then placed in the VFM to determine the heating rate. The heating rate of Type 4 solder with silicon die attached was compared to the average heating rate of solder without any die attached. The comparison can be seen in Figure 3-5.

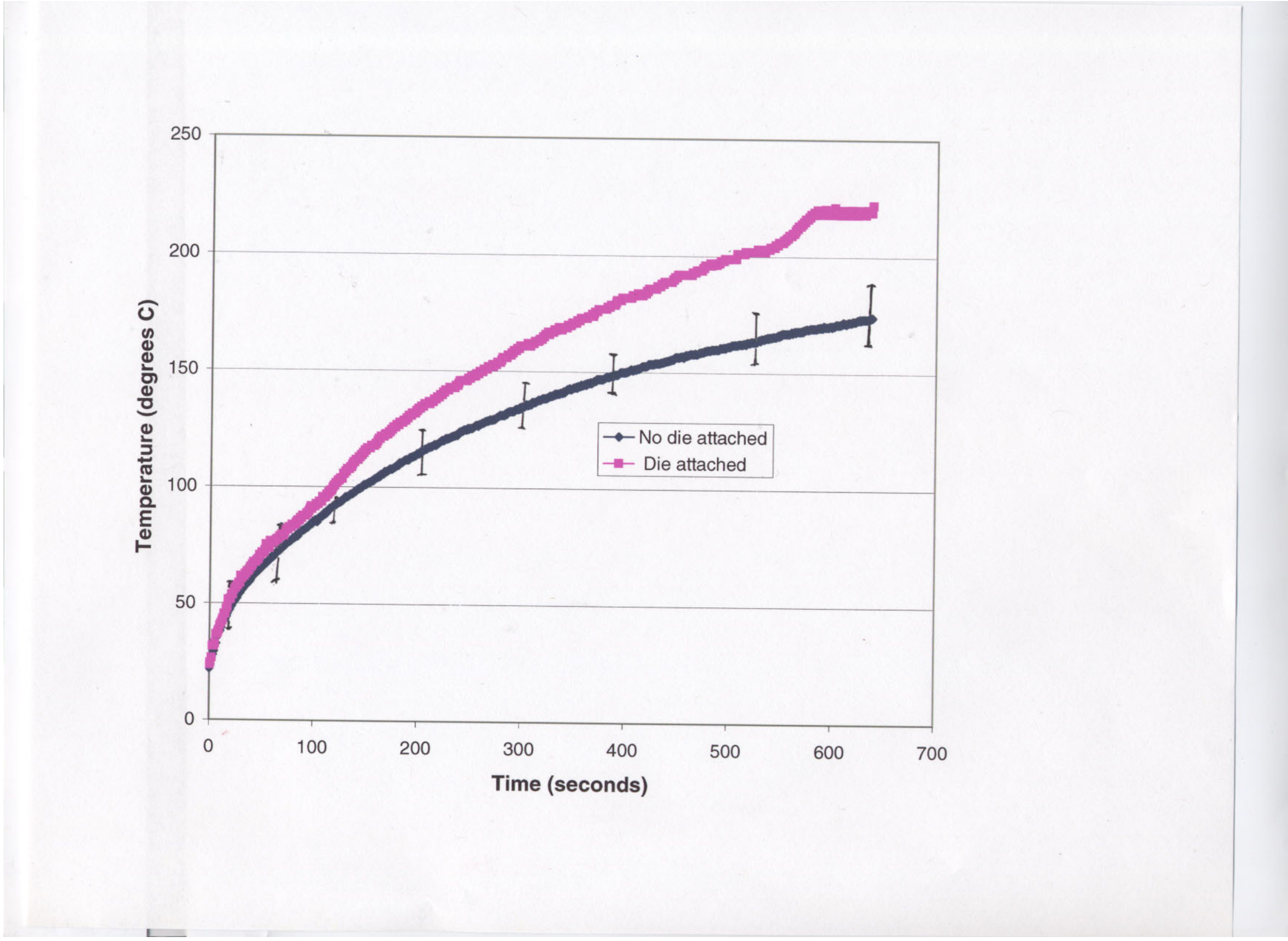

Figure 3-5- Comparison of the heating rate of substrate with die attached and no die attached.

The sample with a silicon die attached was heated to 220°C and held at that temperature for 60 seconds. The sample with the die attached heated significantly faster than the average heating rate of Type 4. The silicon die caused the assembly to heat faster because of its absorption of microwaves. As the silicon heated, that heat was transferred to the solder underneath and around it.

3.2 Reflow Temperature Results and Discussion

In order to determine how well solder reflowed at the low temperatures used, the solder was first reflowed per the Indium Corporation's suggested profile in a thermal oven to provide a control sample. The recommended reflow temperature was between 229° and 250°C for 30 –90 seconds. The temperature chosen for this research was 230°C for 60 seconds. Indium Corporation suggests a ramp rate of no more than 30-60°C/minute.

Initially, a duplicate sample was placed in the VFM to reflow with a ramp rate of 60°C/minute. Despite using the same heating profile, the board degraded. The most severe degradation occurred along the outer rim of the sample. According the temperature and power profile, the power spiked to 500 W. At this same point, the temperature also jumped from 130°C to 160°C. BT board degradation occurs at 250°C.

However, the center of the sample had not reached that temperature based the pyrometer reading. A contact thermocouple was used to measure the temperature in the middle of the samples. It confirmed that the pyrometer reading was accurate. Due to atmospheric heat loss, the interior of the samples heated through VFM processing is significantly hotter than the surface. While this is one of the major reasons for uniform heating, it can occasionally lead to furnace runaway and hot spots. [19] As these hot spots occur, the board temperature also spikes. This could lead to areas of the board outside of the pyrometer viewing area to exceed 250°C, thus causing the board to burn. The setting was changed to constant power as opposed to constant ramp rate. This allowed samples to be processed at up to 500 W without consistently burning.

Several samples were processed without a nitrogen purge to determine if an inert atmosphere allows the samples to heat more rapidly without burning occurring. Although the desired increased heating rate occurred, the majority of samples processed without a nitrogen purge degraded. The temperature, however, reached 230°C very quickly in comparison to samples that were heated with the nitrogen purge under otherwise identical conditions. This may be due in part to oxidation occurring.

Previous results showed that when copper patterns had edges, such as squares, lines, etc., there was a higher incidence of degradation. The degradation took place around the edges of the metal patterns. [34] The copper patterns in this research were circles, so as expected, burning did not occur around the perimeter of the circles to the same degree as sharp corners. The circle pattern reduces the electric field intensity and results in less degradation. Most of the burning propagated along the edges of the BT board. A possible explanation is that in the corners of the square samples the electric field is higher, allowing burning to occur. Another sample was sanded to round the corners of the board. Reducing the electric field at the sharp corners was thought to be a possible solution to the burning along the edges of the sample. Making round corners helped, but it did not completely solve the problem. Occasionally degradation occurred in samples with round corners. For those samples, degradation occurred around the center of the boards. Apparently the sharp corners are not the primary factor in the burning of these samples.

There appeared to be another factor that contributed to board degradation. Occasionally as samples were being prepared, some copper bridging (lines of copper between pads) occurred during the etching process. If there was bridging between the copper pads, degradation tended to occur at the point of bridging. Every sample with extra copper outside of the pattern area degraded. One of the purposes of using a plate resist is to prevent bridges from occurring. [12] However, if it is not properly applied, bridging can still occur. Occasionally during screen printing, there was too much residual plate resist left on the squeegee causing strands of the resist to be deposited. Because copper is a reflective material, extra copper present reflects the microwaves. In addition, Sung found that when placing samples on a quartz plate during VFM processing (as was done in this research), as the copper area on the board surface decreased, the heating rate increased. [34] The small areas of copper caused through bridging or that remained from the etching process were not covered by solder balls. These areas are significantly smaller than the patterns used in Sung's research. These very small areas of copper may cause the heating rate of the board to increase more rapidly than the area being measured where the solder was present. This in turn can cause degradation to occur. Based on this information, extra care was taken when making samples. Only samples with no bridging and no large copper areas outside of the patterns were used. Significant improvements were seen after that point

Several ramp rates were investigated to determine the best rate at which to process the samples. After degradation occurred with a 30°C/minute ramp rate, a 15°C/minute ramp rate was found to be satisfactory for processing samples.. The faster ramp rate needed higher power to be applied in order to maintain the necessary heating rate. This often resulted in power and temperature spikes that caused degradation. The shape of the curve of the 15°C/minute ramp rate matched the shape of the 30-60°C/minute curve of the reflow profile recommended by Indium Corporation. The 15°C/minute ramp rate profile is shown in Figure 3-6. It can be compared to the Indium profile (Figure 2-3). The total processing time was 16 minutes.

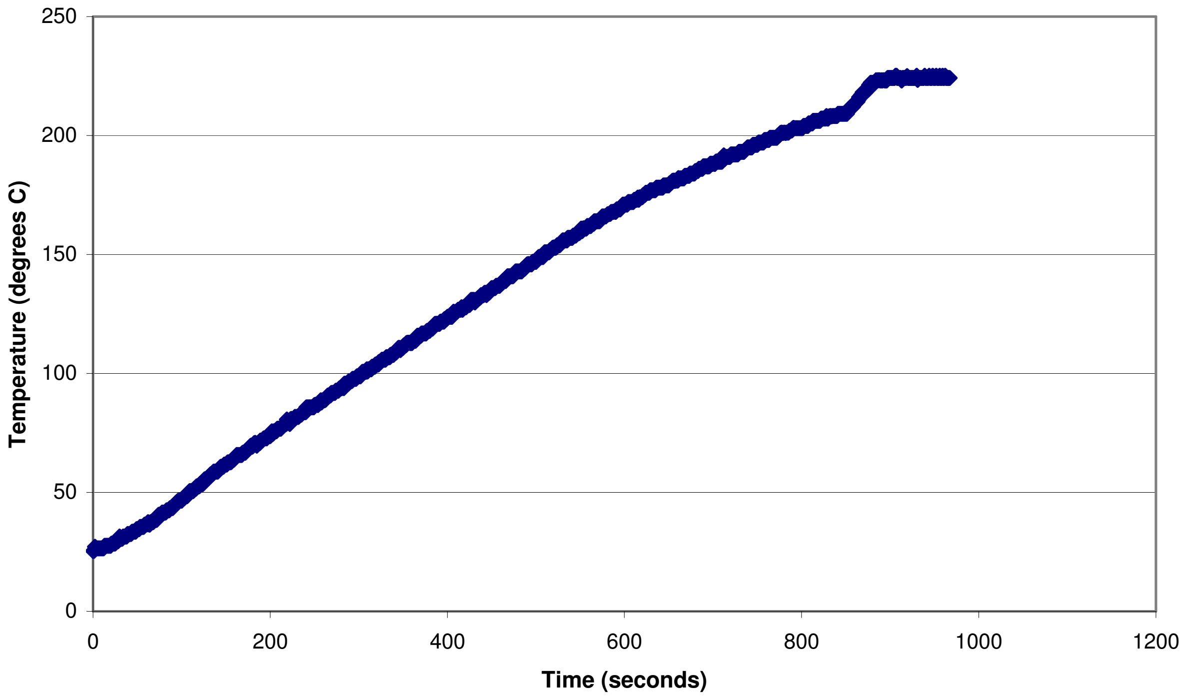

Figure 3-6 VFM reflow profile of Sn/Ag/Cu solder paste.

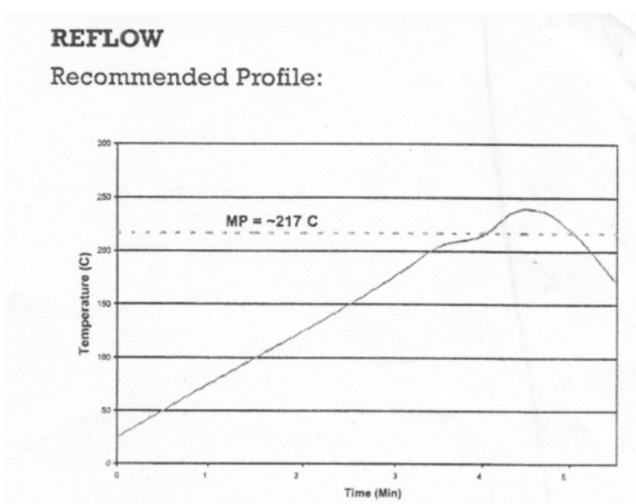

Figure 2-3 Indium Corporation's recommended solder reflow profile [31]

To determine the lowest temperature at which the lead-free solder would reflow, samples were reflowed in the variable frequency microwave starting at 230°C with a hold time of 60 seconds. If reflow occurred, then a new sample was reflowed at a temperature that is 2°C lower. A summary of the results for Type 3 is found in Table 3, and the results for Type 4 are found in Table 4.

Table 3- Type 3 reflow temperatures; * denotes some reflow occurred.

Temperature (°C)	Did Total Reflow Occur?
230	Yes
228	Yes
226	Yes
224	Yes
222	Yes
220	No*
218	No

Table 4- Type 4 reflow temperatures; * denotes some reflow occurred.

Temperature (°C)	Did Total Reflow Occur?
230	Yes
228	Yes
226	Yes
224	Yes
222	Yes
220	Yes
218	No*
216	No

Type 3 had some non-uniform reflow at 220°C. No reflow occurred at 218°C. Type 4 had some reflow occur at 218°C, but no reflow occurred at 216°C. Therefore, the lowest temperature for processing Type 4 is 220°C, and 222°C is the lowest reflow temperature for Type 3 solder. Solder reflowing at 220°C has great ramifications. The reflow temperature of eutectic Sn-Pb solder is also 220°C. [9] This means that the temperature drawback for lead-free solder paste can be overcome through the use of VFM processing. The temperature that the solder is reflowed in the VFM may actually be more significant because based on temperature calibration of the VFM. Between 205°C - 230°C, the actual temperatures are between 5-7 degrees lower that the reading given by the pyrometer. When reflow occurs at a lower temperature, it allows the amount of time that the sample must be held at high temperatures to be minimized. This is illustrated in Table 5. The time necessary for the samples in Table 1 to reach the lowest reflow temperatures (222°C for Type 3 and 220°C for Type 4) are compared to the total processing time. As seen in the table, each sample would have had to endure less time at elevated temperatures.

Table 5- Time necessary for sample in Table 1 to reach lowest reflow temperature for solder paste type.

Solder Paste Type	Maximum Temperature Reached (°C)	Total Processing Time (minutes)	Initial Time To Reach Lowest Reflow Temperature (minutes)
3	229	69.6	29.5
3	223	103.6	87.2
3	223	113.1	101.2
3	206	34.0	N/A
4	225	21.7	19.9
4	221	93.4	82.1
4	206	33.5	N/A

3.3 Shear Stress Results and Discussion

During their lifetime, solder joints will be subjected to many temperature cycles and experience a variety of forces. Therefore, it is important to know whether or not VFM processed solder will be able to withstand the high forces at the same level that solder reflowed in a furnace can. Silicon die were attached to the BT board using the Type 4 solder. Half of the samples were reflowed using the VFM, while the remaining samples were reflowed in the Lindburg furnace. The VFM samples were reflowed at 220°C. The furnace samples were reflowed at 230°C, based on the temperatures recommended by Indium Corporation. Both sets of samples were ramped to their maximum temperatures at a rate of 15°C/minute. Visually, there is no difference between solder reflowed in the VFM and solder reflowed in a furnace. Using the Instron, load versus extension data was taken. A load was applied to solder balls to determine the load necessary to shear the solder from the substrate. The shear stress of the furnace and VFM cured samples were compared.

From the load the shear stress, τ, was able to be determined through the use of Equation 2-6. The shear strain, γ, was calculated using Equation 2-7. In addition, the shear modulus, G, was also calculated from Equation 2-9.

$$\tau = \frac{P_s}{A_s}, \qquad \textbf{Equation 2-6}$$

$$\gamma = \tan\alpha = \frac{\Delta y}{z_0}, \qquad \textbf{Equation 2-7}$$

$$G = \frac{\tau}{\gamma}. \qquad \textbf{Equation 2-9}$$

The average of the results are compiled in Table 6. Error analysis was also performed on the data though the use of standard deviation. The Instron was also used to shear silicon die attached with solder from the board. The load was applied to the die in this case. The shear stress, shear strain, and the shear modulus were calculated. The loads necessary to shear the die were extremely low. They should have been comparable to the load necessary to shear the solder ball. This in turn resulted in unnaturally low stress and strain values. These results lead to the conclusion that the solder beneath the silicon die did not in fact reflow. Visually, the solder looked to have reflowed, but it is highly probable that total reflow did not occur.

Table 6- Shear stress and strain data

Material Sheared	Reflow Method	Load Necessary to Shear (N)	Stress (MPa) at maximum load	Strain at Fracture Point	Shear Modulus (MPa)
Solder ball	VFM	0.536	7.590	5.247	1.447
Solder ball	Furnace	0.545	7.719	4.860	1.588

Based on the research, a comparable load was necessary to shear the VFM reflowed solder from the substrate. This result was possible even though the solder was reflowed at a temperature that was 10°C lower than the temperature used for reflow in conventional furnace. This is a positive result for VFM processing because it shows that using a lower processing temperature for VFM reflow will still result in comparable reliability to traditional reflow. This decrease will be of extreme value to the industry. The industry's biggest concern with lead-free solder is the high processing temperatures. This study shows that by using VFM processing, not only can lead-free solder be reflowed at less than 250°C causing less thermal stress on electronic package components, but that the quality and reliability of the solder does not have to compromised by the lower processing temperature.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The purpose of this research is to determine if using variable frequency microwave can improve the reflow of lead-free solder paste. As the world moves towards becoming lead free, the microelectronics industry has put effort into developing lead-free solder. One of the major drawbacks to this is the higher reflow temperatures necessary to reflow this solder, and the problems this increased temperature causes.

The heating rate of different particle size solder was examined. Based on the results of the experiments performed, the difference in the heating rates of Type 3 (25-45 μm) and Type 4 (20-38 μm) solder paste is negligible. This is most likely due to the fact that the particles sizes are so similar and overlap. The particles are randomly distributed in the solder paste, so any given cross-section of Type 3 and Type 4 could have the same size particles.

The heating rate of solder on substrates with different surfaces was also compared. Both types of substrates had copper patterns on the top surface. However, one substrate had a single sided copper surface, while the other had a full copper bottom surface. The sample with the bare bottom surface heated significantly faster than the substrate with the copper bottom surface. The copper on the bottom surface acts as a heat sink. This corresponds with previous research. On a similar note, a sample with silicon die attached to the top surface, heated at a much faster rate than samples without die attached. The silicon heats faster, transferring that heat to the solder underneath.

Microwave energy has been shown to reduce the temperature necessary to process materials. Experiments were performed to determine if it would have the same effect on the solder paste. The ramp rate for furnace processing (60°C/minute) was attempted for the VFM. However, this resulted in the samples burning. Eventually, a ramp rate of 15°C/minute was determined to be effective. Type 3 solder paste was sufficiently reflowed at 222°C. However, the Type 4 solder paste could be sufficiently reflowed at 220°C. This is significant because this is a standard reflow for eutectic Sn-Pb solder.

One of the goals of this research is to determine if the joints created by VFM reflowed solder is as reliable as solder reflowed in a traditional method. Solder balls that were reflowed by both VFM and a furnace were subjected to loads necessary to shear them from the substrate. The differences in the necessary loads were negligible. This means that VFM solder is comparable to the furnace reflowed solder.

Solder joints were created using silicon die attached to the substrate. Samples were again subjected to loads to shear the die from the substrate. These results proved to be inconclusive. The load necessary to shear the die was extremely lower than the load necessary to shear the solder ball. Based on this fact, it is believed that the solder did not completely reflow.

This research proves that variable frequency microwave reflowed lead-free solder perform as well as traditionally reflowed solder paste. In addition, VFM allows solder to be reflowed at a lower temperature, thus eliminating one of the major obstacles to making lead-free solder an attractive option in the worldwide reduction of lead use in the microelectronics industry.

4.2 Recommendations for Future Work

It is recommended that further reliability research be conducted at lower VFM processing temperatures. Being able to reflow lead-free solder at a lower temperature will only be a reality if other reliability tests show that VFM reflow is comparable or superior to the reliability of traditional processing methods.

Different substrates should also be examined. This may help in the area of the boards burning. Another type of substrate may not degrade randomly the way the BT boards did throughout this research. Also a different substrate may contribute to less thermal runaway and hot spots. These things may help to make variable frequency microwave reflow of no-lead solder paste an industry-wide reality.

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