Optimisation of a Surface Mount Technology Process Using a SnAgCu Lead-Free Alloy

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Declaration

I declare that I am the sole author of this thesis and that all the work presented in it, unless otherwise referenced, is my own. I also declare that this work has not been submitted, in whole or in part, to any other university or college for any degree or qualification.

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Abstract

The impending introduction of lead-free solder in the manufacture of electrical and electronic products has presented the electronics industry with many challenges. European manufacturers must transfer from a tin-lead process to a lead-free process by July 2006 as a result of the publication of two directives from the European Parliament. Tin-lead solders have been used for mechanical and electrical connections on printed circuit boards for over fifty years and considerable process knowledge has been accumulated.

Extensive literature reviews were conducted on the topic and as a result it was found there are many implications to be considered with the introduction of lead-free solder. One particular question that requires answering is; can lead-free solder be used in existing manufacturing processes?

The purpose of this research is to conduct a comparative study of a tin-lead solder and a lead-free solder in two key surface mount technology (SMT) processes.

The two SMT processes in question were the stencil printing process and the reflow soldering process. Unreplicated fractional factorial experimental designs were used to carry out the studies. The quality of paste deposition in terms of height and volume were the characteristics of interest in the stencil printing process. The quality of solder joints produced in the reflow soldering experiment was assessed using x-ray and cross sectional analysis. This provided qualitative data that was then uniquely scored and weighted using a method developed during the research. Nested experimental design techniques were then used to analyse the resulting quantitative data. Predictive models were developed that allowed for the optimisation of both processes.

Results from both experiments show that solder joints of comparable quality to those produced using tin-lead solder can be produced using lead-free solder in current SMT processes.

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CHAPTER 1

RATIONALE AND IMPLICATIONS OF LEAD-FREE SOLDERING

1.0 Introduction

This chapter discusses the issues associated with tin-lead solder and explains the reasons why lead-free soldering is being introduced into electronics manufacturing. These include legislation, environmental, health and safety risks and market benefit. The chapter also discusses the wide range of implications the introduction of lead-free soldering will have on the electronics manufacturing industry. The overall objectives of the project are also outlined.

1.1 Background to the Introduction of Lead-Free Soldering

Over the years the electronic industry has experienced an enormous amount of change. One of the most recent changes is the imminent introduction of lead-free solder to electronic manufacturing. This study investigates the effect of using a lead-free solder in the screen-printing process and reflow soldering process for micro Ball Grid Arrays (μBGA's).

The introduction of lead-free solder is being driven by legislation for the abolition of lead from electrical and electronic goods and the environmental risks from waste electrical and electronic equipment (WEEE). Another major driver is the perceived marketing benefit of supplying lead-free electronic goods. In todays environmentally conscious society, companies want to portray a greener image to increase their market share. This stems from growing consumer awareness of the harmfulness of lead and the recognition and expectation of "green manufacture".

After almost a decade of debate on the issue, legislation has been introduced by the European Union to minimise the impact of WEEE and to ban the use of hazardous substances such as lead in the manufacture of new products. Two pieces of European law, the directive on waste electrical and electronic equipment, commonly known as the WEEE directive, and a directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, the RoHS directive, effectively ban the use of lead in electronics manufacturing. This has led to the need for new lead-free solders and the investigation into whether existing processes are suitable for their use. Until now tin-lead solders have been the popular solder of choice. These solders have been used for mechanical and electrical connections on printed circuit boards for over 50 years as Richards (2003) points out. Tin-lead solders have proven characteristics that are suitable for electronic applications such as low melting point, high strength ductility and fatigue resistance, high thermal cycling and joint integrity. This type of information is not yet available for lead-free solder. As a result, extensive testing is required to determine whether solder joints made using lead-free solder is of a comparable quality to that of solder joints made using tin-lead solder.

1.2 Risks

Historically, the normal treatment of WEEE is to consign it to landfill. This poses a serious environmental and health risk. There is a threat that lead leached from this waste will pollute water supplies and soils. Lead is a suspected carcinogen and if ingested is poisonous, according to Lewis (1992). The nervous system, blood system, and kidneys are the major organs affected if this happens. Owing to strong evidence of the toxicity of lead, its use in paint and petrol has been banned for several years. There is also some level of concern regarding lead in domestic water pipes, plumbing solder, fishing weights and gunshot. According to Lee (1999) approximately 5 million tons of lead is consumed worldwide every year. The gross majority of this, approximately 81%, is used in storage batteries. These do not contribute much to pollution, as they are almost 100% recycled. Ammunition and other lead oxides account for about 10% with solder accounting for 1.3% of the total lead use worldwide. Although this amounts to only 65,000 tons worldwide, most will find its way into landfill sites under current waste management practices.

The Levels of WEEE are expected to rise in this age of technological advancement that encourages consumers to keep up with the latest technology. In the EU it is estimated that the volume of WEEE is growing at a rate of between 3 and 5 per cent. This is almost 3 times faster than that of household waste and is putting pressure on Europe's limited landfill capacity.

Ireland's Environmental Protection Agency (EPA) conducted extensive research to try and predict levels of WEEE. Wilkinson *et al* (2001) estimated that in the period 1991 to 2005 between 505,000 and 1,040,000 tonnes of WEEE will be produced. In 2001 an estimated 35,000 to 82,000 tonnes of WEEE was produced in Ireland of which only 2,412 tonnes was recycled. Ireland's growing economy coupled with its increasing population has increased the consumption of goods including electrical and electronic products. This, married with an underdeveloped waste management system and recycling infrastructure means that Ireland has a lot of work to do before we can transpose the requirements of the directive into our laws. As it stands and according to the legislation the EU has granted Greece and Ireland a 24-month extension to some of the deadlines in the directive because of their recycling infrastructure deficits.

1.3 Legislation

The first attempt at introducing legislation to ban lead from electronics came in 1990 with the, "Lead Exposure Reduction Act S2637 and S729" in the US Senate, according to Suganuma (2002). This bill included a proposal to ban all lead-bearing alloys. After intense lobbying by the electronics industry, which argued correctly at the time that there was no identified technical alternative to tin-lead solder, the proposed ban was removed from the bill.

In their report released in May 2001, the EPA reviewed the national legislation of member states in the EU regarding WEEE. It found that The Netherlands, Austria, Germany, Belgium, Denmark, Italy and Sweden all operated some form of take-back schemes for electronic goods. Most of these schemes were introduced during the 1990's. According to Lee (1999), Denmark, Sweden, Norway, Finland and Iceland signed a statement in 1994 to phase out lead in the long run. Sweden has led the way in Europe for the elimination of lead from products. In 1997 the Swedish government released a press statement that identified lead as an element that will be eliminated from products over the next 10 years. The

Sweden Environmental Quality Objectives state that any new products introduced in that country should be largely free from lead by 2010.

Section 29 of Ireland's Waste Management Act 1996 allows for the provision of producer responsibility if the government sees fit. There is no specific legislation on WEEE or the use of hazardous materials such as lead in electrical and electronic equipment in this country yet. However the laws in all EU countries will be influenced by the enactment of legislation on these matters by the European Parliament and Council. On the 13th of February 2003 a directive on waste electrical and electronic equipment, commonly known as the WEEE directive, and a directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, the RoHS directive, became part of European law. These directives have been designed to address the serious environmental concerns that WEEE represent. The legislation calls for recycling and recovery of the waste. The environmental impact of WEEE will be minimised by improving the environmental performance of end of life equipment by banning the use of hazardous substances in the manufacture of new products. The objectives of both pieces of legislation are as follows:

WEEE Directive Article 1

> The purpose of this Directive is, as a first priority, the prevention of waste electrical and electronic equipment (WEEE), and in addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment, e.g. producers, distributors and consumers

and in particular those operators directly involved in the treatment of waste electrical and electronic equipment.

RoHS Directive Article 1

> The purpose of this Directive is to approximate the laws of the Member States on the restrictions of the use of hazardous substances in electrical and electronic equipment and to contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment.

The RoHS Directive compliments the WEEE Directive and aims to further reduce the environmental impact of electrical and electronic goods when they reach the end of their useful lives. The main points of the new Directives are:

- The four heavy metals, lead, cadmium, mercury, and hexavalent chromium, and the brominated flame retardants PBB and PBDE will be banned from **1st July 2006**.
- Collection for recovery of at least 4kg per inhabitant by 31st December 2006 at the very latest. This is to be implemented through take back systems and collection facilities.
- For WEEE arisings from private households, producers will bear the costs of collection, recovery, and disposal of new products. This is to be introduced by 13th August 2005.
- For historical waste, i.e. products on the market before the Directive became law, producers can use collective or individual collection, recovery, and disposal schemes.

- To minimise the disposal of WEEE as unsorted municipal waste and to facilitate its separate collection, producers are required to label their products with the symbol shown in Annex IV of the Directive.
- Member states are to encourage the design and production of equipment which facilitates easy dismantling and recovery and provides for reuse and recycling of the components and materials.

The Directives became European law in February 2003 and were to be transposed in to EU member state laws by the 13th August 2004. The categories of equipment covered by the WEEE & RoHS directive is extensive as can be seen in Table 1.1.

1. Large household appliances	6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
2. Small household appliances	7. Toys, leisure and sports equipment
3. IT and telecommunication equipment	8. Medical devices (with the exception of all implanted and infected products)
4. Consumer equipment	9. Monitoring and control instruments
5. Lighting equipment	10. Automatic dispensers.

Table 1.1 Categories of electrical and electronic equipment covered by the WEEE & RoHS directives

1.3.1 Activities in Japan

Activities in Japan regarding the move towards lead-free goods were well advanced before the publication of the EU legislation. Plumbridge (2000) reported at that time Japanese electronics companies were ahead of their European and American counterparts in terms of their well-defined timescales for the introduction of lead-free solders into their processes. Individual companies have their own specific targets for lead free introduction. For instance since October 1998 Panasonic have been shipping 40,000 mini-disc players per month with lead–free solder used in the printed circuit boards. Although companies have defined their own timescales they have done so in collaboration with JEITA (Japan Electronics and Information Technology Industries Association). This association is a body inaugurated in November 2000 by combining JEIDA (Japan Electronic Industries Development Association) and EIAJ (Electronic Industries Association of Japan). Table 1.2 shows the timescales some manufacturers employed for the change over to lead-free soldering according to an ESPEC Technology Report in 2002. Although there is no legislation outlawing the use of lead in solder, Japan has introduced legislation that is similar to the WEEE directive. The Japanese Home Appliance Recycling Law has been in force since April 2001. Matsuo (1999) outlines the impact of this law. The product items subject to the law are television sets, electric refrigerators, electric washing machines and air conditioners. In accordance with the law, consumers bear the recycling expenses and have to deliver their electronic waste to the retailer. The retailer takes the waste equipment to the manufacturer who has the responsibility of recycling it in the proper manner. To accomplish this home appliance manufacturers have built recycling plants throughout

Japan. Goosey (2003) points out that the Japanese have demonstrated that there are sound commercial benefits from moving to lead-free manufacturing.

Manufacturer	**Items Targeted**
Matsushita Electric Industrial Co., Ltd.	Eliminate all lead by end of 2002 Applied to compact MD players by Oct 199 Applied to VCR's by end of 1999 Applied to cassette players by Jan 2000
NEC Corporation	Reduce 1997 volume by half by March 2001 Eliminate all lead by Dec 2002 Applied to pagers by December 1998 Applied to Note PC's by October 1999
Hitachi Ltd.	Reduce 1997 volume by half by March 2002 Eliminate all lead in in-house manufacturing by March 2002. Eliminate all lead in Hitachi Group by March 2004
Fijitsu	Lead-free by 2002
Sony	Lead-free in Japan by 2001 Lead-free elsewhere by 2002
Mitsubishi	Lead-free by 2005

Table 1.2 Japanese OEM's changeover to lead-free timescales

1.4 Market Benefit

There is more to the imminent introduction of lead-free soldering than environmental risks, safety risks and legislation. The use of nontoxic materials in manufacture can improve the public image of a product and a company. In today's society, consumers are increasingly aware of the dangers of toxic materials such as lead. Richards (1999) states that consumers in industrialised countries are showing preferences for products that are perceived to be green. Companies are keen to turn this to their advantage and nobody more so than Japanese OEM's. Since introducing their lead-free mini-disc player, Panasonic have reported an increase in marketshare for that product from 4.7% to 15% according to Goosey (2003). By 2001 Panasonic had 188 lead-free products available.

A quick review of most consumer electronics manufacturers websites shows pages dedicated to lead-free products. Almost all will devote space to details of their environmental policies with regard to their products. For example Sanyo have introduced a certification system that provides for "Environmentally harmonious products" and "Environment conserving products". The former are products that consume less energy, use less harmful substances and have a minimal impact on the environment. The latter are products that improve the environment by using clean energy or by reducing waste.

Japan has the advantage of already producing lead-free products. This allows them to refuse to import goods that do not meet their environmental standards. It will force European manufacturers who export to Japan to build lead-free products. Ericsson recognised this and released a list of banned and restricted substances in June 2003. They state that the purpose of this list is, *"to meet existing and anticipated legal requirements and market demands"*. Not surprisingly lead is one of the substances included on the list.

With all of the developments in the last number of years regarding lead-free manufacturing, it means that electronics manufacturers must develop environmentally friendly production techniques and products in order to remain competitive.

1.5 Implications of the Changeover to Lead-Free Manufacturing

The changeover to lead-free electronic manufacturing requires consideration of issues other than just the lead-free alloy itself. Issues from purchasing through the manufacturing process to inspection must be considered. Manufacturers must give thought to the entire process before implementing the changeover. Outlined below are general considerations and more specific issues that must be taken into account.

1.5.1 General Considerations

Lead-free soldering requires higher process temperatures than the existing lead alloy. Major efforts have been made by various consortia to introduce a direct replacement for tin-lead solder. However no drop-in replacement exists.

Current manufacturing technologies are equipped for the tin-lead solder melting temperature of 183°C. The melting temperature of possible lead-free alternatives ranges from 199°C up to 227°C. This has serious implications for all the processes involved in electronics manufacturing. Processes such as the stencil printing process for depositing solder paste on circuit boards and the reflow soldering process used to form the final solder joint will need to be investigated. Manufacturers will need to evaluate these current processes using lead-free solder to determine whether solder paste deposits and solder joints of similar quality to those produced using tin-lead solder are achievable.

1.5.2 Lead-Free Alternatives

Use of and research into lead-free solder has been going on for some time. Many lead-free solders exist, some of which have been patented by solder manufacturers and manufacturers of electronic equipment. Initial research into lead-free solders centred on trying to recommend one out of the many that is universally suitable. Ideally this would then be used as the industry standard. The thinking behind this is to minimise the amount of set-up time and process changes in SMT manufacturing. However it is now widely accepted that there is no drop-in replacement for tin-lead (SnPb) solder. From the range of possible alternatives available there is growing consensus for the tin-silver-copper (SnAgCu) alloy. However, this has not been recommended as a drop-in replacement. It seems that the equipment manufacturer will decide on which solder to use based on the product.

Many working groups have selected a number of promising lead-free solders and evaluated them. Bath *et al* (2000) selected six such solders and then assessed each to determine their relative advantages and disadvantages. The criteria used for selection of the solder was as follows:

- If possible stay with ternary alloys or less. Quartenery alloys can present control difficulties.
- The new alloy should be near eutectic. For example, it should have a large pasty range during cool-down.
- Avoid using a patented alloy if possible, so industry freedom of action is guaranteed.

- Using the best knowledge available, choose an alloy with no possible environmental issues.

This criteria coupled with the criteria recommended by Lee (1999) can be used when selecting a lead-free solder to test. Lee's criteria were as follows:

- Non-toxic
- Available and affordable
- Narrow plastic range
- Acceptable wetting
- Material manufacturable
- Acceptable processing temperature
- Form reliable joints

1.5.3 Purchasing and Design

Purchasing should be made aware of what lead-free parts and materials are available. Any purchased parts should be compatible with the manufacturing process in question. Seelig and Suraski (2003) recommend a close working relationship between purchasing and design to ensure that suitable lead-free parts are available for new products at the design stage. Other obstacles that purchasing could encounter are single source suppliers for a part, parts that are not entirely suitable for the application in question, change in lead-times, more expensive parts or no parts at all.

Lead-free solders have different thermal and physical properties than tin-lead solders. It is very important for designers to be aware of this to avoid unexpected localised thermal expansion of components or cracking of solder joints for example.

1.5.4 Components and Component Finishes

Component manufacturers have concerns regarding the transition to lead-free assembly. This is due mainly to the higher process temperatures and unknown reliability characteristics of the new alloys. Some components are highly susceptible to high temperature damage such as electrolytic capacitors. These may need to be hand-assembled after reflow. Other components that may be affected are electromechanical devices, light emitting diodes, and connectors. There is also the increased risk of components "popcorning". This occurs if moisture gathers inside the component and vapourises at the higher temperatures needed for lead-free soldering. This can cause internal stresses to the component resulting in cracking. These cracks could potentially provide paths for contaminants to enter the component package and compromise reliability. A solution may be to pre-bake components prior to assembly as suggested by Seelig and Suraski (2003). Other solutions suggested are to employ more stringent storage methods and conditions.

Lead can exist in three different forms in components:

1. Lead in functional materials in piezoelectric elements, capacitors, glass, fuses etc.
2. Lead in solder used in internal connections within the components.
3. Lead in the solder-plating surface finishes on the leads of components.

Lee (1999) claims that technologically it will be very difficult to substitute the lead used in functional materials in components. Lead used in internal connections within the components can be replaced with lead-free alloys. The only concern as Richards (2003) points out is the melting point hierarchy of the alloys used. Care must be given to which alloys are selected for the first tier connections for die attachment and second tier connections for module attachment. These must not reflow when the package is being soldered to the PCB (Printed Circuit Board).

Lead-free solder plating of component leads has advanced in the last number of years. Bradley *et al* (1999) define a good component lead finish as one that provides a solderable surface by protecting the core metal from oxidation during the assembly process. Ideally oxidation should also be prevented during storage prior to use.

Traditionally components have been plated with a tin-lead alloy as Richards *et al* (1999) explains. This provided good solderability and wetting for the tin-lead soldering process. Barbini (2001) claims that the component lead finish for lead-free assembly will be dictated by the lead-free alloy chosen by the manufacturer. Compatibility between the lead finish and the lead-free alloy is key. Solderability and wetting must be adequate to ensure a reliable solder joint. There are numerous lead-free finishes available as Goosey (2003), Barbini (2001) and Bradley *et al* (1999) point out.

1.5.5 Flux

Fluxes are chemicals that assist in the soldering process. The basic function of a flux according to Judd and Brindley (1999) is to clean any contaminants from the metal surface to be soldered and leave it covered to prevent further contamination. It also aids wetting by reducing surface tension and allowing the molten solder to flow more freely. Another property of flux is to act as a vehicle for heat transfer to the solder joint during soldering. Flux in solder paste has the added function of cleaning the solder powder particles. Hwang (1996) points out that it must also obtain complete coalescence of the solder powder particles during reflow.

Existing flux formulations provide these properties to the industry for the eutectic tin-lead solder. These flux formulations need to be evaluated for their effectiveness in meeting the requirements of the new lead free alloys. Any new chemicals used as flux need to be stable at the higher temperatures required for the new alloys.

For surface mount devices that are hard to clean under, a suitable no-clean flux is preferable. Flux residue must not cause any shorts, contamination or corrosion. Richards *et al* (1999) reported that at that time the development of new fluxes concentrated on rosin-free, VOC free environmentally sound products. They state that compatibility between soldering temperature profile and chemical and physical properties of the specific flux or paste is critical in achieving the best soldering results and the highest level of cleanliness. In general a VOC – free, water based flux is recommended as Barbini (2001) points out.

1.5.6 Reflow Process Changes

Reflow soldering is the process by which a PCB printed with solder paste and populated with components is passed through a reflow oven and heated using particular a heat profile. Solder paste is a combination of flux and solder particles which melt and then solidify during the process to form the mechanical and electrical connections between the PCB and the components. The higher temperatures required for lead-free reflow soldering pose a number of potential problems. Existing reflow ovens may not have the capability to reach the required peak temperatures. Bradley *et al* (1999) advised that electronic manufacturers should work closely with equipment suppliers to address this. New ovens are available for lead-free reflow. These ovens include innovations such as changes in heating zone configurations. The new zone configurations mean an increase in the number of heating zones and a decrease in the size of the individual zones. This allows for greater process control while maintaining the higher temperatures needed.

Board warpage is also a potential problem depending on the materials used in the PCB. The new reflow oven designs offer a centre support rail in the critical areas, reflow and cooling zones, to counteract this.

It is possible that existing machinery can operate at the higher temperatures. However, some may need significant modification or adjustment. Another issue for the reflow process is the smaller process window. By using nitrogen to solder under an inert atmosphere, Goosey (2003) claims that several process improvements are achievable. A wider process window, improved wetting and improved solderability are among the benefits. Richards (2003) reports that Japanese manufacturers have noticed reduced voiding in BGA's when inerting is used. Voids are cavities inside solder joints caused by gases released during reflow soldering or flux residues trapped in a solder joint before the solder solidifies.

In general it is advised to use convection reflow as infrared and vapour reflow soldering will not reach the required temperatures and will have lower throughput respectively. Convection reflow methods were used in this study. Concern has also been expressed at the increased energy consumption that will be needed to reach the higher temperatures.

1.5.7 Rework

The rework and inspection of lead-free solder joints is considerably different from the traditional tin-lead joints. The higher temperatures needed for lead-free soldering shrinks the process window considerably. The margin between the minimum temperature for reliable reflow soldering and the maximum temperature for materials safety has significantly decreased. It is important that rework thermal profiles are kept closely similar to the original reflow profiles. This is because a minimum of two reflow cylces is required; removal and replacement per rework and these extra thermal cycles could have adverse effects on components and boards. If thermal profiles for rework are kept similar to original reflow profiles the performance and reliability of the equipment for the original design should not be compromised.

Other important issues for rework of lead-free solder are highlighted by Goosey (2003). These include using the correct lead-free solder alloy as there are known incompatibilities between certain alloys. If alloys are mixed because of rework it could possibly compromise reliability. There is also the issue of encountering several lead-free solders in service instead of one standard alloy. Each one will have its own process requirements and conditions. This could mean that assemblers will have to establish specific procedures for each type of solder.

1.6 Key to Successful Lead–Free Assembly

Successful lead-free assembly will be achieved if manufacturers pay attention to the impact that lead-free solder will have on each aspect of the process. In this study two of the main processes involved in electronic manufacturing, namely solder paste printing and reflow soldering are investigated. Both processes were evaluated using a chosen lead-free and tin-lead solder and the results were compared. Micro ball grid arrays (µBGA's) were used to populate the printed circuit boards. BGA's are surface mount electronic devices that have gained a large market share in the electronics packaging industry due to their compactness and large number of inputs and outputs.

1.7 Project Objectives

This project examines two surface mount technology (SMT) processes; the solder paste printing process and the reflow soldering process. Introducing lead-free solder into the electronics manufacturing environment raises many questions, the most important being:

- Are the new materials suitable for use in existing processes?
- Can existing processes provide results equal to or better than tin-lead solder when a lead-free alloy is used?
- What are the optimum process settings to repeatedly produce these good results?

The goal of this project was to investigate and to address these issues. More specifically the objectives were:

- To determine if lead-free solder could be used in existing SMT processes
- To plan, select and conduct appropriate experimental designs on the solder paste printing process and reflow soldering processes
- To determine whether results are comparable to tin-lead solder.
- To establish the optimum process settings for the chosen lead-free solder

1.8 Conclusion

The introduction of lead-free soldering to electronics manufacturing is inevitable. Legislation combined with market pressure and the growing consumer awareness of the harmfulness of lead has ensured this. As a result, the implications to electronic equipment manufacturers are wide ranging and varied. This chapter has noted and discussed the reasons for the introduction of lead-free soldering and has outlined many of the issues facing manufacturers. The chapter also presents the goals and objectives of this research.

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CHAPTER 2

STENCIL PRINTING

2.0 Introduction

Chapter two introduces surface mount technology (SMT) and its processes. From a review of the available literature it is observed that the process step of stencil printing is the most critical step involved. The chapter examines this process in detail and considers some of the issues involved in stencil printing.

2.1 Surface Mount Assembly

Lee (2002) indicates that the electronics industry has progressed from using through-hole technology (THT) from the 1960's to the 1980's to using surface mount technology (SMT) devices from the mid 1970's to present day. Surface mount devices (SMDs) such as chip scale packages (CSPs), direct chip attach (DCA), and ball grid arrays (BGAs) are currently satisfying the need for higher circuitry density. Passive components such as resistors, capacitors, and inductors are also available as surface mount components and provide large real estate savings on printed circuit boards (PCBs). Other advantages of SMDs over THT include reduced weight and volume, lower cost, and better performance. This has lead to SMT becoming the major assembly technology in electronic manufacturing. The emergence of SMT has brought with it the manufacturing processes needed to assemble surface mounted PCBs. In general there are three major types of SMT board assembly as explained by Prasad (1997). Each assembly type requires its own process sequence and type of equipment. Type I SMT assembly contains surface mount components only. These can be mounted on one or both sides of the board. Typically components on the top-side are reflow soldered first after which the components on the bottom side are reflow or wave soldered into position. Wave soldering is used if the components on the underside are large or heavy. If this is the case adhesives have to be used to secure the components in place resulting in extra steps in the assembly process. Figures 2.1 and 2.2 are typical of a type I board schematic and process assembly.

Depending on the type of flux used, cleaning may or may not be needed. If cleaning is needed, it could be done after the first or second soldering process step or after both. In some cases manufacturers have successfully employed a single cleaning process. If a no-clean flux is used in the assembly, cleaning is eliminated from the process reducing the number of process steps. When components are placed on one side of the PCB only, the assembly would be completed at step 4 of the process flow chart shown in Figure 2.2.

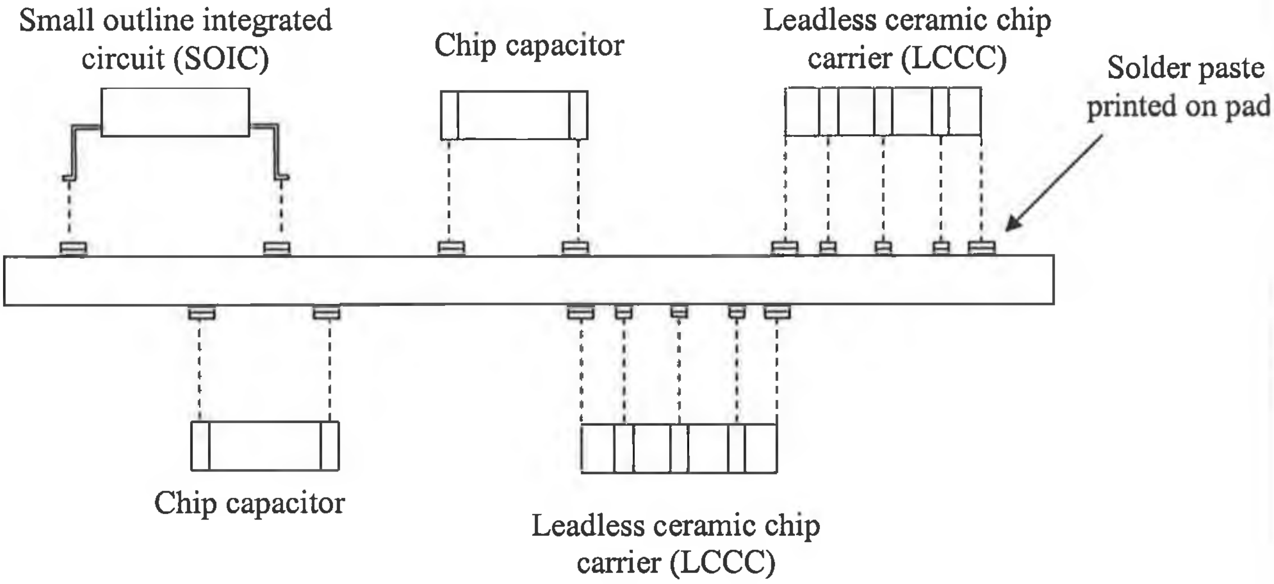

Figure 2.1 Schematic of Type I surface mount PCB

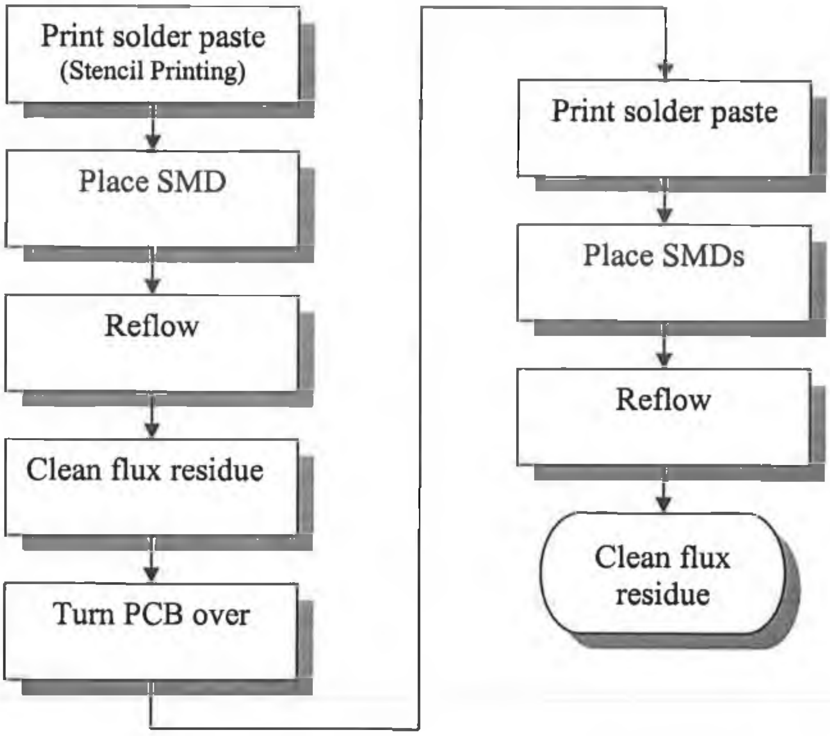

Figure 2.2 Example assembly process for Type I surface mount boards

Type I assembly could be considered the purest form of SMT assembly as only SMDs are used on the boards. Type II and type III assemblies include some through hole components (THCs) as shown in Figures 2.3 and 2.4. Type II assembly has both SMDs and THCs on one side of the PCB and surface mount chip components on the other side. These assemblies offer flexibility in using THCs for some components that aren't yet available as surface mount devices. Type II assemblies however require both wave and reflow soldering. This means extra process steps in the assembly, extra equipment, and ultimately these types of PCB are more expensive to manufacture.

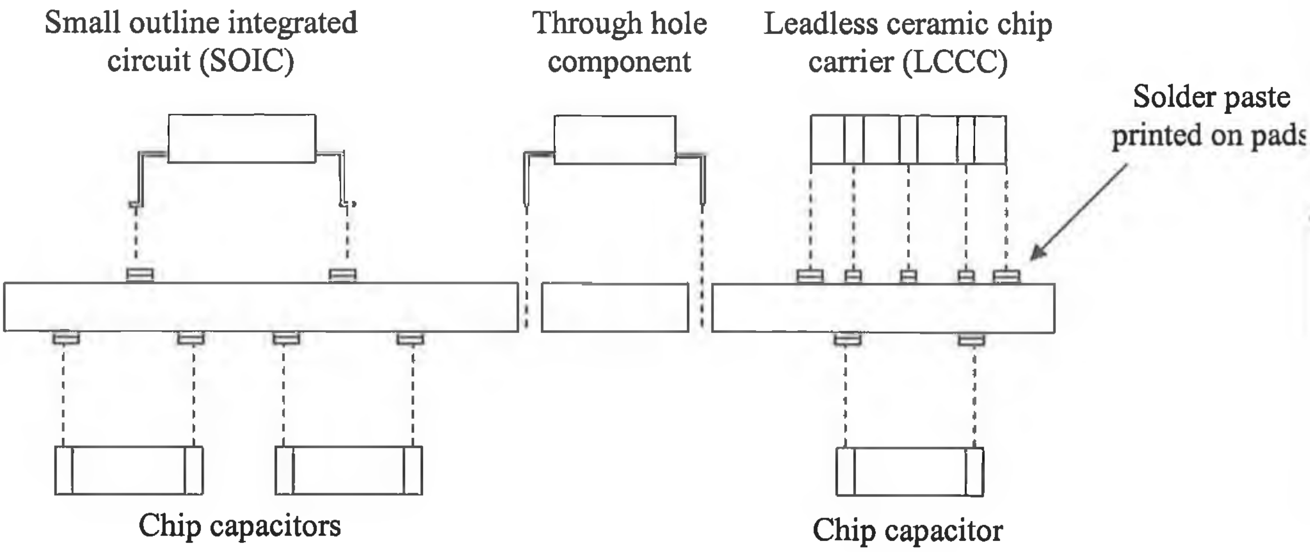

Figure 2.3 Schematic of Type II surface mount PCB

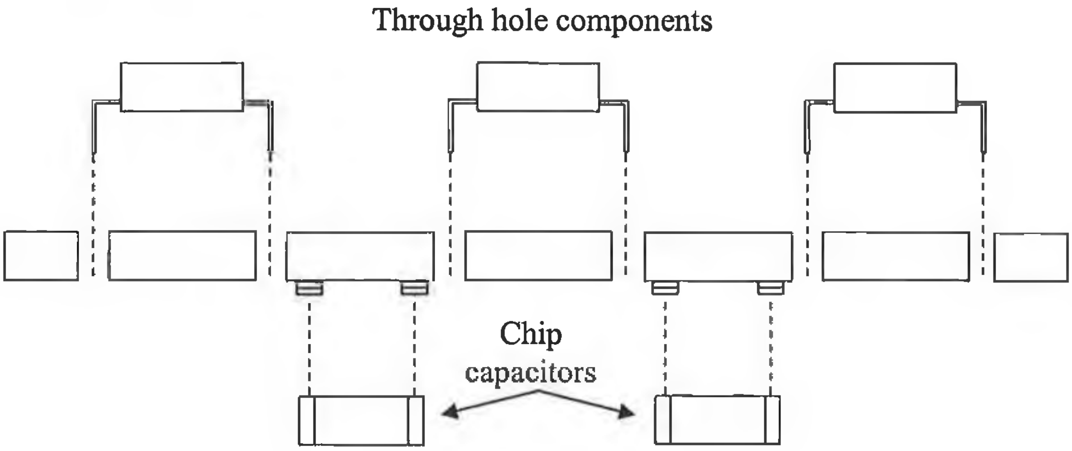

Figure 2.4 Schematic of Type III surface mount PCB

Type III assemblies have THCs on one side of the PCB and surface mount chip components on the other side. These type of assemblies only require wave soldering and are regarded as the first step in the transition from THT PCBs to full surface mount PCBs.

BGAs are typical surface mount devices that have gained a large market-share in the electronics packaging industry. This is due to their compactness and large number of inputs and outputs that facilitates the trend toward smaller and lighter electronic products without the loss of equipment performance. Their attractive characteristics mean they have become integral to many electronic systems from military to consumer applications. Koch (1998) also highlights the fact that BGAs can be processed in a standard surface mount assembly line.

The BGA assembly process is similar to type I PCB assembly comprising the three main process steps of stencil printing, component placement and reflow soldering. At a glance this assembly process appears straightforward but there are many variables within each step that require consideration. The process step considered the most critical is the initial step of stencil printing. Montgomery *et al* (2000), Gopalakrishnan and Srihari (1999), and McPhail (1996) all report that over 60% of defects in a surface mount assembly process can be attributed to the stencil printing process. If the initial step of the SMT assembly process is prone to high defect rates then the degree of control on the remaining process steps will have little effect. Any defects generated in the stencil printing process will add increased costs downstream due to rework and lower yield. As a result the stencil printing process can be considered the most important process step in the process and warrants careful attention for the introduction of lead-free solder. It has often been said that the solder joint was formed before you ever got to the reflow oven.

2.2 Stencil Printing Process

Solder stencil printing is the process by which solder paste is deposited onto component pads on a PCB before component placement as explained by Judd and Brindley (1999). After component placement and the subsequent reflow soldering processes, the resulting solder joint serves as the electronic and mechanical connection between the electronic component and the PCB pads. The solder paste is deposited onto the component pads on the PCB using a stencil that has etched openings called apertures. The apertures match the land patterns of the components that are placed on the PCB after printing. The PCB is mechanically positioned beneath the stencil to precisely align the land patterns on the PCB with the apertures. A squeegee rolls the solder paste over the stencil filling the apertures. The squeegee then shears off the paste in the apertures as it moves over the stencil. After a print pass or print stroke every aperture is filled with the solder paste and the PCB is mechanically seperated from the stencil to leave a freestanding solder brick or solder deposit on each of the PCB pads. Figure 3 depicts a stencil printing process.

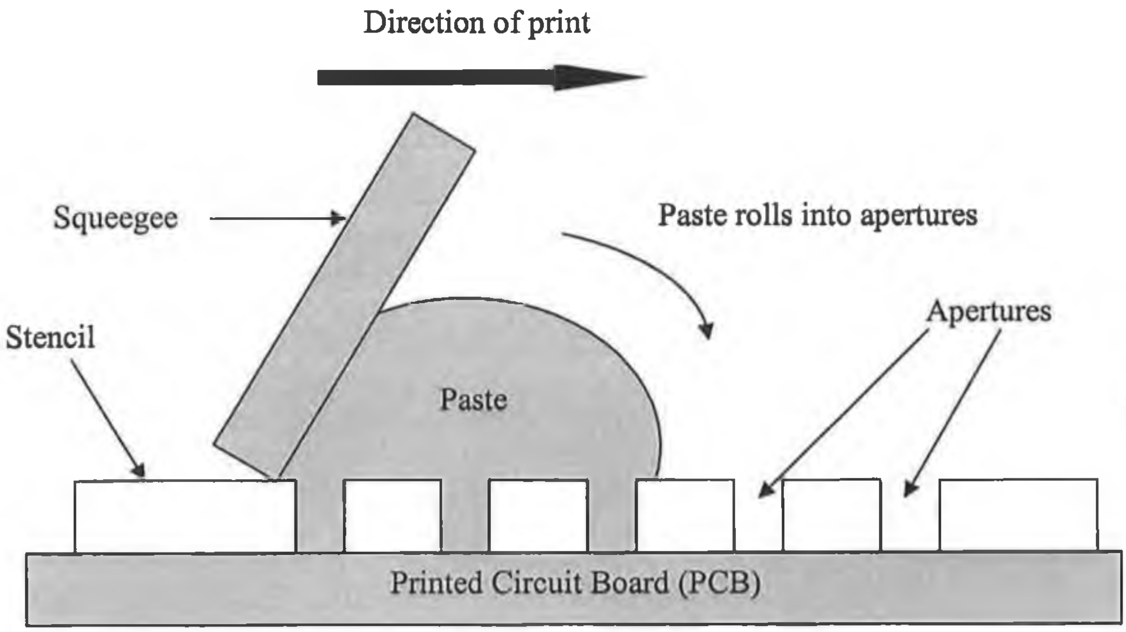

Figure 2.5 Stencil printing process diagram

Houston *et al* (2002) characterised stencil printing in four sub-processes. These were the paste roll over the stencil, aperture filling, separation of the stencil and PCB, and post-print paste behaviour. Although stencil printing appears straightforward, when it is studied the process is quite complex. Clouthier (1997) claims there are 39 different variables spread out over five areas within the stencil printing process. In reality it is difficult to control all 39 variables but to optimise the stencil printing process a careful review of the complete process is necessary and the key variables identified. The five areas include the PCBs, solder paste, stencils and squeegees, printers and the measurement equipment. The environment in which the process is conducted could also be included as Haslehurst and Ekere (1996) point out.

2.2.1 PCB's

PCB manufacturers control a number of variables that could affect the quality of the paste deposition on a circuit board. Coulthier (1997) lists a number of issues the PCB manufacturers must have control over to help ensure a good stencil printing process. Unevenness in the PCB caused by incorrect solder masking, raised board legend or board warpage during the manufacturing process can all cause the stencil not to seal to the pad sufficiently. This could result in smearing of the solder paste and the generation of short circuits downstream in the process. Accuracy of pad locations on the PCB to match the devices that will eventually populate the board is crucial as is the location of fiducials for alignment purposes. According to Coleman (2002), PCB stretch or shrink is another important factor. If the PCB is susceptible to any stretching or shrinking then pad to aperture accuracy will be affected causing a mis-registration of solder paste.

2.2.2 Solder Paste

The rheology of solder paste is recognised as the important factor when paste deposition is the issue. Solder paste consists of three main constituents, namely the solder alloy powder or particles, the flux system and the carrier system that binds the flux and solder alloy together. Durairaj *et al* (2002) discuss the microscopic structure of these constituents that influences solder paste rheology. Attributes such as solder particle size distribution, metal content, inter-particle forces and particle flux interactions can affect the flow of solder paste. They suggest however that the microscopic structure and individual constituents can be ignored and the solder paste considered as a homogenous mixture categorised by macroscopic properties such as density and viscosity. Lee (2002) outlines the importance of solder paste viscosity in relation to stencil printing. The viscosity needs to be high enough during storage and handling to maintain the suspension of the heavy metal powder or particles in the flux system and low enough during stencil printing so that the paste can flow easily through the stencil apertures. After printing the viscosity needs to be high enough to hold the shape of the deposited solder brick and to avoid slumping or bridging with neighbouring solder bricks. It also needs to be non-tacky enough to be released through a stencil aperture and sufficiently tacky to hold the component in place after component placement. Solder paste viscosity generally decreases with increased temperature. Heat generated by the ambient temperature and heat generated by the solder paste role during stencil printing are two sources of variability in solder paste viscosity. Reidlin and Ekere (1999) maintain that solder paste temperature could rise by 2°C during printing but due to the advancements made in solder paste manufacturing in the last decade the rise in temperature has little effect on the viscosity of solder paste.

Desired solder paste rheolgy is application dependent and McPhail (1996) and Burr (1998) provide good rules of thumb when deciding on what paste to choose. Choice of solder ball size for solder paste is important as it allows for good paste release from stencil to pad. McPhail (1996) suggests a method that will help provide paste release and prevent clogging. He advocates the rule that 3 solder balls of maximum solder ball diameter used in the solder paste should locate both horizontally and vertically into the finest stencil aperture. Burr (1998) agrees with the principle of the rule but recommends that it should be 3.5 balls that fit across the aperture. He also states that square apertures help with maintaining a consistent opening over round apertures.

2.2.3 Stencils

Johnson and Boyes (2002) identify material, thickness, image pattern, and aperture size as the key elements of stencil design. Clouthier (1997) describes the various materials available for stencil production and outlines the pros and cons of each material in relation to the common manufacturing techniques. Stencils are mostly manufactured using one of three technologies according to Hale (1999). The three technologies are:

Chemical Etching:

Chemical etching is a subtractive process that removes some of the existing material to form the aperture openings. Chemically etched stainless steel stencils are created by laminating the material with a photo resist on both sides and then exposing it to a phototool. The apertures are then etched from both sides simultaneously. Advantages of chemical etched stencils are the relatively low cost and fast throughput time. The disadvantages are the lack of repeatability of aperture widths and the creation of a knife-edge contoured type finish on the aperture walls. Such finish can impede the paste release from a stencil but can be counteracted through a post process procedure called electropolishing according to Gloukler (2001).

Laser Cutting

Laser cutting like chemical etching is a subtractive process. A programmable laser cuts the aperture opening in the material surface based on xy coordinate positioning. Electropolishing might be required as laser cutting can cause a rough cut on the aperture wall. The advantages of laser cut stencils over chemically etched stencils are the repeatability of the aperture size, the elimination of a knife edge finish and the there is no misalignment of top and bottom side phototools. The main disadvantage is the laser cuts each aperture individually. Therefore the more apertures the more time consuming and expensive the process becomes.

Electroforming

Electroforming is an additive process. The stencil is constructed by imaging photoresist on a substrate where the apertures are intended and then plating nickel, atom-by-atom, layer-by-layer around the resist to create the stencil. Any desired thickness or aperture shape is possible making electroforming the most flexible of the available processes. However throughput time and costs are high.

In general chemically etched stencils are suitable for applications where the smallest component pitch is 0.6 mm or higher. Laser cut and electroformed methods should be considered when dealing with pitch dimensions of 0.50 mm or under. Pitch size is the distance between component leads or solder balls and is component specific.

Stencil thickness is determined by the pitch size of the component. For example, Burr (1998) recommends a 0.005mm to 0.006 mm thickness for BGAs. It is important that the stencil thickness is correct so that enough solder paste is deposited on the PCB pad.

The ideal scenario during the stencil printing process is all the paste that filled the apertures during a print cycle releases from the aperture walls and attaches to the PCB pads after PCB and stencil separation. According to Coleman (2000) the ability of the paste to release from the inner aperture walls depends on three major factors:

1. The print area ratio
2. The aperture side wall geometry
3. The aperture wall smoothness

The print area ratio is the area beneath the aperture opening divided by the area of the inside aperture wall. The generally accepted guideline for sufficient paste release is for the ratio to be greater that 0.66. When the stencil separates from the PCB, the paste release experiences competing forces, does the paste transfer to the PCB pad or stick to the aperture sidewalls? If the print area ratio is 0.66, the probability is the process will achieve 80% paste release or better. Aperture sidewall geometry and smoothness is dependant on the stencil technology employed and also affects paste release. An aperture with a knife-edge finish will not release as much paste as a straight walled finish at a given print or ratio. Similarly a laser cut stencil with an electropolished finish will have smoother sidewalls than a non-electropolished laser cut stencil and will release a higher percentage of paste at a given ratio.

Stencil cleaning is another important issue to consider when trying to achieve a defect free stencil printing process. Different cleaning techniques are required for clean and no-clean solder pastes. It is essential that the cleaning technique removes all solder paste residue from the stencil without damaging it. Excess paste remaining on a stencil can create solder balls or clog the apertures, which will cause skipping. Clouthier (1996) outlines the different types of stencil cleaning techniques available taking into account the process, environmental, health, and safety considerations. Manufacturers that have successfully adopted no-clean technology have eliminated cleaning from their process. However it may be necessary to clear away any excess material from time to time if it accumulates on the stencil. Bixenman and Pitarys (2001) discuss cleaning for fine pitch stencils and recommended that the bottom side of a stencil should be cleaned to prevent small amounts of solder paste drying and accumulating around the base of the aperture. This could be argued for all surface mount stencil printing and not just fine pitch printing.

2.2.4 Squeegees

Prasad (2001) states that squeegee wear, pressure, and hardness contribute to the final print quality of the solder paste. Two commonly used materials for squeegees are polyurethane (PU) and metal. The hardness of these materials contributes to the respective wear and pressure effects of each squeegee type.

The edge of a squeegee should be sharp but hard enough to endure the thousands of print strokes it will encounter. Ideally it should wear uniformly to maintain the print characteristics over the squeegees life. Generally PU squegees tend to wear more easily than metal squeegees because they are softer. However a metal squeegee can cause wear on the stencil.

An incorrect squeegee pressure could result in unacceptable paste prints. If it is too low it could skip over an aperture resulting in an open joint downstream and if it is too high it could cause smeared prints or damage the squeegee or stencil. Also, a softer squeegee coupled with excessive pressure tends to scoop out the solder paste from any wide apertures. However as Lau and Yeung (1997) point out a softer squeegee is more suitable to dual thickness stencils where apertures for fine pitch and standard surface mount components are present on the one stencil. The softer stencil can move over any contours more easily than a metal squeegee. A metal squeegee is more suitable to fine pitch printing. A general requirement of all squeegee types is that they are resistant to the various components of the solder paste and any other materials it comes into contact with.

2.2.5 Stencil Printing Machines

Settings of stencil printing machine parameters have a profound effect on the final print quality of the solder paste. Table 2.1 lists the typical parameters that can be controlled on these machines. Authors such as Poon (1999) and Gopalakrishnan and Srihari (1999) have conducted experiments on these machine parameters to optimise the respective processes. Results have shown that various parameters have an effect on print quality depending on the application.

Squeegee pressure	Separation speed
Printing speed	Print pressure
Squeegee angle	Number of print strokes
Temperature	Snap off distance
Cleaning Interval	Print direction

Table 2.1 Typical stencil printing machine parameters

It can be seen from the above discussions on stencil printing why it must be considered as one of the crucial processes in electronic manufacturing. As a result it warrants special attention and experimentation when introducing lead-free solder.

2.3 Conclusion

This chapter documents a review of the stencil printing process and discusses the factors involved in achieving a good quality solder paste print definition. The chapter also explains where stencil printing fits into the overall SMT manufacturing process. The review of the literature indicates that the stencil printing process is the most critical step in the SMT manufacturing process. As a result of this it was deemed important as part of the study to conduct experimentation on this process.

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CHAPTER 3

EXPERIMENTATION ON A STENCIL PRINTING PROCESS

3.0 Introduction

In the previous chapter it was explained how important the stencil printing process is to electronic manufacturing. As a result, part of this project evaluates the stencil printing process to investigate whether lead-free solder can produce results equal to or better than tin-lead solder. This chapter comprehensively outlines the planning, designing, conducting, and results of a designed experiment on the stencil printing process.

3.1 Experimental Design Planning

Montgomery (2001) describes experimental design as a series of tests in which purposeful changes are made to the input variables of a process so that changes in the output response may be observed and reasons for the change identified. Experimental design techniques are useful for process and product design, development and improvement. Most manufacturing processes are ideal for making use of this powerful analytical tool, as they have many input variables and identifiable key quality characteristics on the output that provide experimenters with readily available factors and responses.

The planning of experimental designs that precedes any experimentation is as important as the execution of the experiment itself. Hahn (1977) and Barton (1997) discuss basic considerations and practical aspects of planning experiments. Montgomery (2001) provides a seven step approach to planning and designing experiments. The first three of these steps listed below constitute the pre-experiment stage. Coleman & Montgomery (1993) present useful suggestions on how to flesh out these important steps.

- Recognition and statement of the problem
- Choice of factor levels and range
- Selection of response variable

After the planning stage, a design is selected, the experiment is then conducted and the resulting data is analysed. To ensure the success of this study on the stencil printing process, extensive planning and review was carried out in the pre-experiment stage.

3.2 Objectives

Stencil printing is a crucial step in the surface mount manufacturing process. The introduction of lead-free solder into the electronics manufacturing environment raises a number of questions, namely:

- Are the new materials suitable for use in existing stencil printing processes?
- Can an existing process provide sufficient solder paste release for a good print definition equal to or better than that achieved by tin-lead solder?
- If it can, what are the optimum process settings to repeatedly produce these good results?

The challenge facing manufacturers is one of discovering whether their existing processes will work with the new material and if it does what are the new parameter settings to optimise the process output.

3.3 Factors, Levels and Ranges

When deciding on the factors for the stencil printing experimental design, the whole printing process was considered together with knowledge of the particular process being experimented upon and best manufacturing practises. Previous experiments conducted on various other stencil printing processes were reviewed to examine what factors, and levels, and ranges were used. Poon (1999) performed an extensive screening experiment on eight process and material factors identified as potentially significant to the output quality of a stencil printing process. A metric based on the volume of solder paste printed and the number of stencil printing defects determined by visual inspection were the responses chosen by Poon. A 2^{8-3} fractional factorial was used in Poon's design and the eight factors included in the experiment are listed below. Sometimes temperature and humidity are difficult to control factors, however in this experiment they were considered controllable factors due to the type of equipment being used.

- Printing speed
- Squeegee angle
- Temperature of printing chamber
- Viscosity of solder paste
- Cleaning interval
- Separation speed
- Humidity of printing chamber

Poon's experiment found temperature and cleaning had the most significant effects on the response. Several other experiments used similar process and material factors along with other factors that were suspected causes of variation on the response being examined. In their study on process development for ball grid array assembly, Gopalakrishnan and Srihari (1999) included paste type and the stencil thickness as factors. Gagne *et al* (1996) also used these factors along with squeegee pressure, squeegee speed, temperature and humidity. Gopalakrishnan and Srihari (1999) also used the size of the stencil apertures as did Pochareddy *et al* (2000).

Snap off, that is the distance between the stencil and PCB, was another factor deemed important enough by some to experiment with. Montgomery *et al* (2000) set levels of 0.01 inches and 0.04 inches for snap off in their experiment while the levels Manjeshwar *et al* (2002) used for this factor was 0 inches and 0.005 inches. Montgomery *et al* (2000) found snap off to be a significant effect on the mean solder volume of solder paste deposits.

From a review of available literature it is clear that squeegee pressure, separation speed, and printing speed are common factors in most experimental designs conducted on stencil printing processes. Process knowledge and best manufacturing practises would agree that these are the most important factors. Durairaj *et al* (2001) identified these factors as the key process variables when dealing with stencil printing processes. Other factors in designed experiments on stencil printing process are selected depending on the process under test and the objectives of the particular project.

The factors selected for this experiment were based on available literature such as Poon (1999) and Durairaj *et al* (2001) and knowledge of the printing process. Table 3.1 lists the factors and levels used.

	Factor	*Low Level*	*High Level*
A	Print Speed	10.8 mm/sec	13.2 mm/sec
B	Squeegee Pressure	3.6 kg	4.4 kg
C	Separation Speed	10%	15%
D	Snap off	0mm	1.0mm
E	Cleaning Interval	Every 5 Boards	Every 10 Boards
F	Solder Paste	Lead-Free	Tin-Lead

Table 3.1 Factors for stencil printing experimental design

Some of the factors required additional clarification such as what constituted a cleaning process and what were the solder pastes to be used. The process engineers decided a cleaning process would consist of an underside clean and blow out of the stencil and it was decided that the type of solder pastes to be used were a 95.5Sn 3.6Ag 0.7Cu (Kester R910) lead-free alloy and a standard 63Sn 37Pb (Kester 256) alloy for the tin-lead solder. The type of solder paste was included as a factor in order to examine the effect lead-free solder paste has on the process in comparison to tin-lead paste.

3.4 Experimental Response

It was desired to select a measurable response that would provide data regarding the amount of solder paste applied during the process. Solder paste height and solder paste volume were therefore selected as the responses. Most experimental designs conducted on this type of process have used similar responses. The IPC-7095 (2000) standard recognises paste height and paste volume as being the key responses in the solder stencil process. Rajkamur *et al* (2000) give details regarding the importance of solder paste deposit height. If the height is too low there will be insufficient solder to produce a good solder joint and if it is too high it could cause bridging with neighbouring solder joints causing a short and immediate failure.

It was also decided to measure a second type of response. It is always useful to minimise variation in any process. A competitive advantage can be gained from producing many parts with few defects so it stands to reason that minimising variation in any quality characteristic is important. As a result, in addition to considering the solder paste height and volume, height variability and volume variability were also investigated to develop a robust process. The variance of both solder paste height and volume was considered as the measure of dispersion. As variance follows a chi-squared distribution according to Wu and Hamada (2000), a natural logarithm (ln) transformation was used to normalize the variance data as per equation (1). The transformed value, (y) was then used as the experimental response.

$$y = \ln\left(s^2\right) \qquad (1)$$

where:

y is the transformed response for height or volume variance

s^2 is the height or volume variance

3.5 Measurement System

Clouthier (1997) lists a number of variables that require consideration when deciding the type of measurement system to use. In this study, a Solder Paste Inspection and Data Analyser (SPIDA) machine capable of automatic paste height measurement and volume calculation was used. Figure 3.1 displays a picture of the SPIDA machine.

Figure 3.1 SPIDA machine for automatic solder paste height measurement and volume calculation

This was a 2 D measurement system and provided a cost effective method of capturing the information from the experiment.

3.6 Experimental Design

A 2_{IV}^{6-2} fractional factorial was chosen as the experimental design with design generators E=ABC and F=BCD. A full factorial would have required 64 runs and thus proved costly. For the purpose of this study the fractional factorial design was considered satisfactory by the project team involved. The fractional factorial selected was a resolution IV design, therefore no main effects were aliased with any other main effect or two factor interactions, but two factor interactions could be aliased with each other. Due to cost and time constraints one replicate of the experiment was run.

3.7 Experiment Set-up

A PCB containing sixteen locations for 100 pin μBGA devices was used as the test board. Test board dimensions were 16cm x 10cm and the layout of the board is shown in Figure 3.2. A Hot Air Solder Level (HASL) PCB finish and Organic Solderability Preservative (OSP) PCB finish were used for the tin-lead solder paste and the lead-free solder paste respectively. A DEK 260 screen printer was used to print the solder paste onto the pads of the test boards.

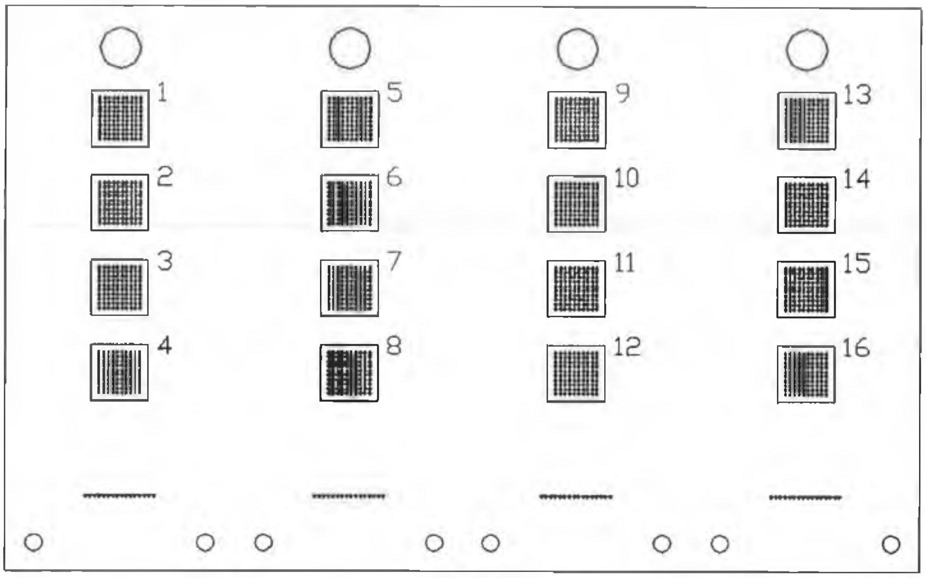

Figure 3.2 Test vehicle layout showing the sixteen BGA locations

3.8 Experimental Runs

The experimental runs were completed in the sequence shown in Table 3.2. The factors for each treatment combination were set and each run was conducted resulting in sixteen PCB's with solder paste deposits. Each printed PCB was numbered and inscribed to distinguish whether it was tin-lead or lead-free paste. A 100-pin μBGA array implies 100 paste deposits per BGA location on each test board. For the purpose of this study five BGA locations were chosen and five paste deposit measurements were recorded on each location. This resulted in twenty-five measurements per PCB.

Standard Order	Run Order	Print Speed	Squeegee Pressure	Separation Speed	Snap Off	Cleaning Interval	Paste
5	1	10.8mm/sec	3.6kg	10.50%	0.5mm	Every 10 Boards	Tin-lead
11	9	10.8mm/sec	4.4kg	9.50%	1.0mm	Every 10 Boards	Lead Free
6	2	13.2mm/sec	3.6kg	10.50%	0.5mm	Every 5 Boards	Tin-lead
13	10	10.8mm/sec	3.6kg	10.50%	1.0mm	Every 10 Boards	Lead Free
9	3	10.8mm/sec	3.6kg	9.50%	1.0mm	Every 5 Boards	Tin-lead
16	4	13.2mm/sec	4.4kg	10.50%	1.0mm	Every 10 Boards	Tin-lead
14	11	13.2mm/sec	3.6kg	10.50%	1.0mm	Every 5 Boards	Lead Free
3	5	10.8mm/sec	4.4kg	9.50%	0.5mm	Every 10 Boards	Tin-lead
7	12	10.8mm/sec	4.4kg	10.50%	0.5mm	Every 5 Boards	Lead Free
15	6	10.8mm/sec	4.4kg	10.50%	1.0mm	Every 5 Boards	Tin-lead
2	13	13.2mm/sec	3.6kg	9.50%	0.5mm	Every 10 Boards	Lead Free
10	7	13.2mm/sec	3.6kg	9.50%	1.0mm	Every 10 Boards	Tin-lead
1	14	10.8mm/sec	3.6kg	9.50%	0.5mm	Every 5 Boards	Lead Free
8	15	13.2mm/sec	4.4kg	10.50%	0.5mm	Every 10 Boards	Lead Free
4	8	13.2mm/sec	4.4kg	9.50%	0.5mm	Every 5 Boards	Tin-lead
12	16	13.2mm/sec	4.4kg	9.50%	1.0mm	Every 5 Boards	Lead Free

Table 3.2 Stencil printing experimental runs

3.9 Analysis Method

Each of the solder paste height and solder paste volume measurements were captured using the SPIDA machine. The actual measurements are shown Appendix A. The mean height and mean volume of the twenty five measurements was used for the analysis and the variance was represented by the variance of the twenty-five measurements for height and volume respectively. The variance data was then normalised using the transformation in equation (1).

It is important to correctly consider the twenty five height and volume measurements as duplicate measurements and not replicates because the five locations chosen from each PCB were processed under the same conditions and at the same time. If these were incorrectly considered as replicate measurements this could lead to incorrect inferences regarding the process as highlighted by O'Neill & Donovan (2004). Experiments using duplicate measurements should be treated as unreplicated designs according to Montgomery (2001). Unreplicated designs underestimate the true error value so many experimenters pool the higher order interactions and use this as an estimate of the error. Another method of analysing unreplicated designs is that of Daniel (1959). He proposed using half-normal probability plots of the effects making the assumption that the data comes from a normal distribution with mean zero. When plotted, nonsignificant effects should lie approximately on a straight line while significant ones tend to lie off the line. The standard method for identifying significant effects in unreplicated experiments has become the normal probability plot but the problem with this method is the subjectivity regarding what constitutes being on or off the straight line.

In their review on methods for analysing unreplicated designs, Hamada and Balakrishnan (1998) state that many of the methods rely on the assumption of effects sparsity. This is the hypothesis that only a small proportion of the factors have effects that are large. They estimate that in practise 20% of effects are significant. The subjectivity concerning what constitutes a point lying off the straight line in a normal probability plot has been the cause for much debate and has lead to the introduction of other methods for analysing unreplicated experiments. Box and Meyer (1986) proposed a Bayesian approach where the experimenter supplies "a priori" probability of a factor being significant and computes, as a function of the results, the "a posteriori" probability of this being the case. Benski (1989) proposed using a Shapiro-Wilk test to indicate the presence of significant effects. Once significant effects were indicated Benski proposed using an outlier test to identify the significant effects. The advantage of Benski's approach is that there is no need for subjective judgment on what points are lying on or off a straight line on a normal probability plot. Other methods of analysis of unreplicated designs include Holms and Berrettoni (1969), Zahn (1975), Lenth (1989), Dong (1993), Schneider *et al* (1993), and Venter and Steel (1996).

Of the methods reviewed by Hamada and Balakrishnan (1998), Lenths method proved to be the most powerful and probably the simplest method of analysing unreplicated experiments. Lenth (1989) devised a formal test commonly known as Lenth's method for analysis of unreplicated designs. The test provides quantitative confirmation of effect significance based on a robust estimator of the standard deviation called the *pseudo standard error* or *PSE* and is described below.

3.9.1 Lenth's Method

It is hard to draw definite conclusions from normal probability plots due to the subjectivity of the method. As a result Lenths method was used to help verify and conclude whether or not the identified factors were in fact significant

Lenth's method of analysis of unreplicated factorials is a quick and easy technique to detect significant effects. The *pseudo standard error* (*PSE)* is calculated in the following way:

Let $\hat{\theta}_i$ denote the estimated factorial effects and s_o the standard error be calculated as,

$$s_o = 1.5 \times median\left|\hat{\theta}_i\right| \qquad (2)$$

The *PSE* is then calculated as,

$$PSE = 1.5 \times median_{\left|\hat{\theta}_i\right| < 2.5 s_o}\left|\hat{\theta}_i\right| \qquad (3)$$

with the *PSE* essentially computed from a trimmed median of $\left|\hat{\theta}_i\right|$ values, as the median is computed using the values of $\left|\hat{\theta}_i\right|$ that are less than $2.5 \times s_o$. The estimated effects are then divided by the *PSE* to create a *t* like statistic, $\left|t_{PSE,i}\right|$. These statistics are compared to critical values of *individual error rate* (IER) as recommended by Ye and Hamada (2000) for factorial experiments to decide on whether an effect is significant.

3.10 Experimental Design Analysis

The results from this experiment were analysed using two of the methods identified for analysis of unreplicated experimental designs. The first method used was Daniel's normal probability plot method. The factorial effects were calculated and plotted on normal probability graphs from which effect significance was estimated. The second method used was that developed by Lenth. This was used to provide confirmation or not of the results observed from the normal probability plots. Section 3.11 presents the analysis and discussion of the results relating to the solder paste height response while section 3.12 does likewise for the solder paste volume response.

3.11 Experimental Design Analysis – Solder Paste Height Response

The normal probability plots for mean solder paste height and solder paste height variance were constructed. Effect significance for each response was identified by examining what effects lay off the straight line. The main effects plots for factors identified as being significant were also constructed. Lenth's method was then employed to provide quantitative confirmation of the results observed from the normal probability plots.

3.11.1 Solder Paste Height Response Analysis – Daniel's Method

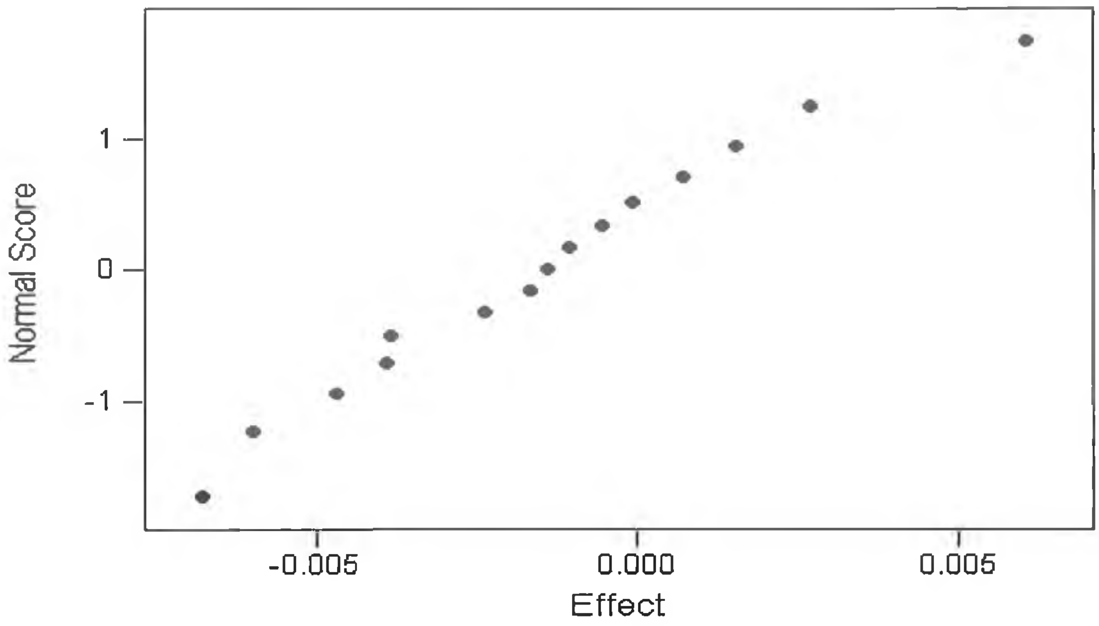

Figure 3.3 Normal probability plot of effects for mean solder paste height

The normal probability plot of effects for mean height in Figure 3.3 depicts a straight line with none of the plotted points lying off the line. This would indicate that there are no significant factors affecting the height response.

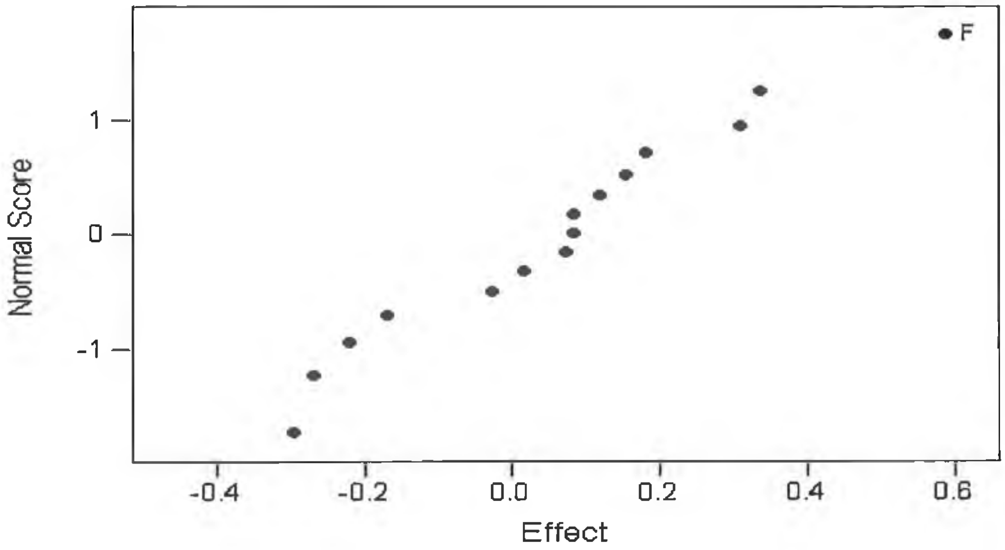

Figure 3.4 Normal probability plot of effects for solder paste height variability (ln)

Examination of the normal probability plot of the effects for solder paste height variability in Figure 3.4 suggests that factor F (paste) lies off the straight line. This implies the paste factor has a significant effect on the height variability response.

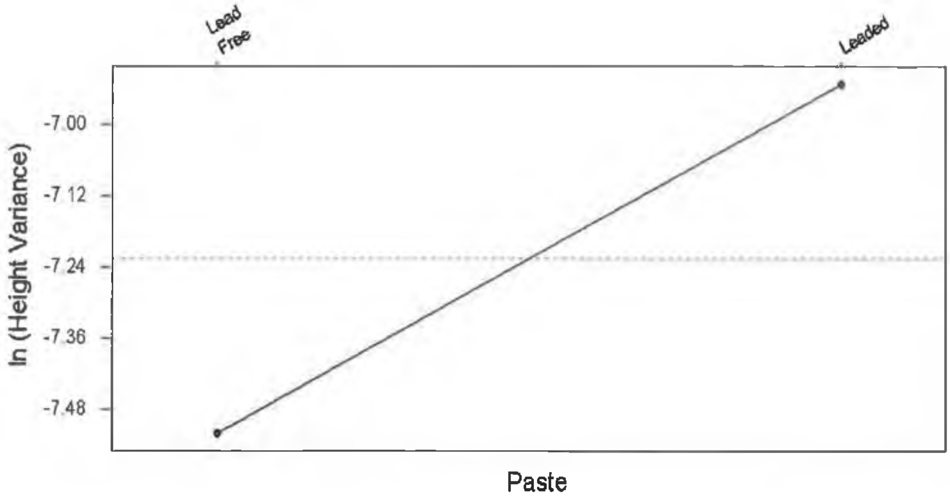

Figure 3.5 Main effects plot for the ln (Height Variance)

Figure 3.5 displays the main effects plot for natural log of the solder paste height variance. It can be seen that the lead-free solder produces less variation in the paste deposit height than the tin-lead solder. Although the *y*-axis of Figure 3.5 shows the transformed (ln) domain, this statement is also valid for the untransformed variance.

3.11.2 Solder Paste Height Response Analysis – Lenth's Method

To determine effect significance the estimated effects and corresponding $|t_{PSE,i}|$ values were calculated and compared to tables of critical values of IER given by Ye & Hamada (2000) and assessed at $\alpha = 5\%$. The critical value at $\alpha = 5\%$ for 15 effects values was 2.16. From examination of the $|t_{PSE,i}|$ values in Table 3.3, none appear to be greater than 2.16. This suggests there are no significant factors affecting mean solder paste height and demonstrates agreement with the corresponding normal probability plot in Figure 3.3.

Term	**Effect**	$\lvert t_{PSE,i} \rvert$
A	0.002685	0.7537
B	- 0.001045	0.2933
C	- 0.001655	0.4646
D	- 0.003815	1.0709
E	0.000715	0.2007
F	0.006055	1.6996
AB	0.001555	0.4365
AC	- 0.004695	1.3179
AD	- 0.002375	0.6667
AE	- 0.005985	1.6800
AF	- 0.003905	1.0961
BD	- 0.001365	0.3832
BF	- 0.000535	0.1502
ABD	- 0.000065	0.0182
ABF	- 0.006755	1.8961

Table 3.3 Estimated effects for mean solder paste height and corresponding $\lvert t_{PSE,i} \rvert$ values

Table 3.4 presents the estimated effects and corresponding $\lvert t_{PSE,i} \rvert$ values for solder paste height variability. From inspection of the table it can be seen that Factor F, i.e. the paste, is significant. This correlates with the normal probability plot in Figure 3.4.

Term	**Effect**	$\lvert t_{PSE,i} \rvert$
A	0.184	0.7258
B	0.336	1.3254
C	-0.221	0.8718
D	-0.268	1.0572
E	0.074	0.2919
F	0.588	2.3195
AB	0.084	0.3314
AC	0.120	0.4734
AD	-0.026	0.1026
AE	0.309	1.2189
AF	-0.297	1.1716
BD	0.085	0.3353
BF	0.156	0.6154
ABD	0.019	0.0750
ABF	-0.169	0.6667

Table 3.4 Estimated effects for solder paste height variability (ln) and corresponding $\lvert t_{PSE,i} \rvert$ values

3.11.3 *Solder Paste Height Response Conclusions*

The results of the stencil printing experiment indicate that current machine settings give less solder paste height variation when using lead-free solder. It is very useful to minimise variation in any process and this experiment shows that lead-free solder produces less height variation than tin-lead solder at the same settings. A real cost saving can be made from having less waste by minimising variation in the process. The fact that the mean solder paste height response showed no significant effects indicates there is no difference when using lead-free solder paste and tin-lead solder paste at current machine settings. The use of Lenth's method confirmed the findings when using the normal probability plots for detecting significant effects.

3.12 Experimental Design Analysis – Solder Paste Volume Response

The normal probability plots for mean solder paste volume and solder paste volume variance were constructed. As before effect significance for each response was identified using normal probability plots and the main effects plots for significant factors were generated. Lenth's method was then employed to examine if quantitative confirmation of the results observed from the normal probability plots.

3.12.1 *Solder Paste Volume Response Analysis – Daniel's Method*

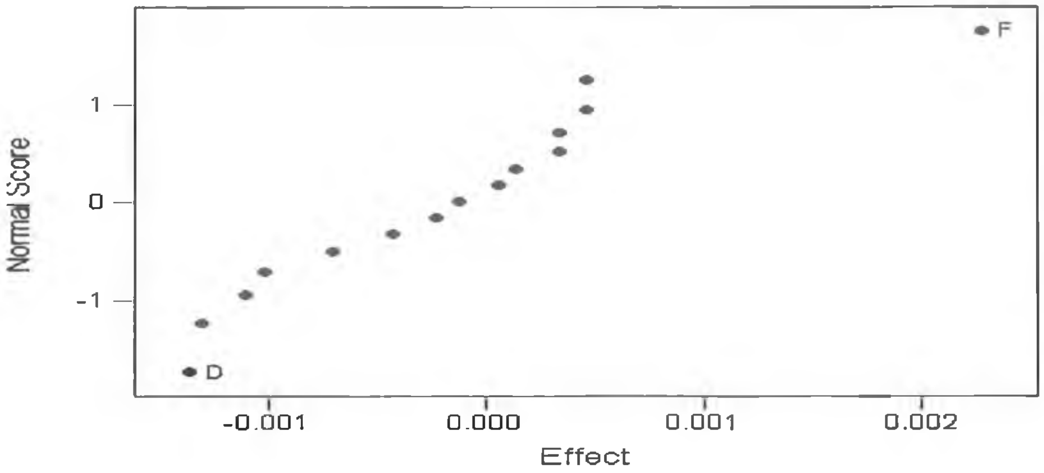

Figure 3.6 Normal probability plot of main effects for mean solder paste volume

Figure 3.6 displays the normal probability plot of main effects for the mean solder paste volume. Factors F and D, i.e. snap off and paste, appear to lie off the line. This suggests that snap off and solder paste have a significant effect on the mean volume of solder paste deposits.

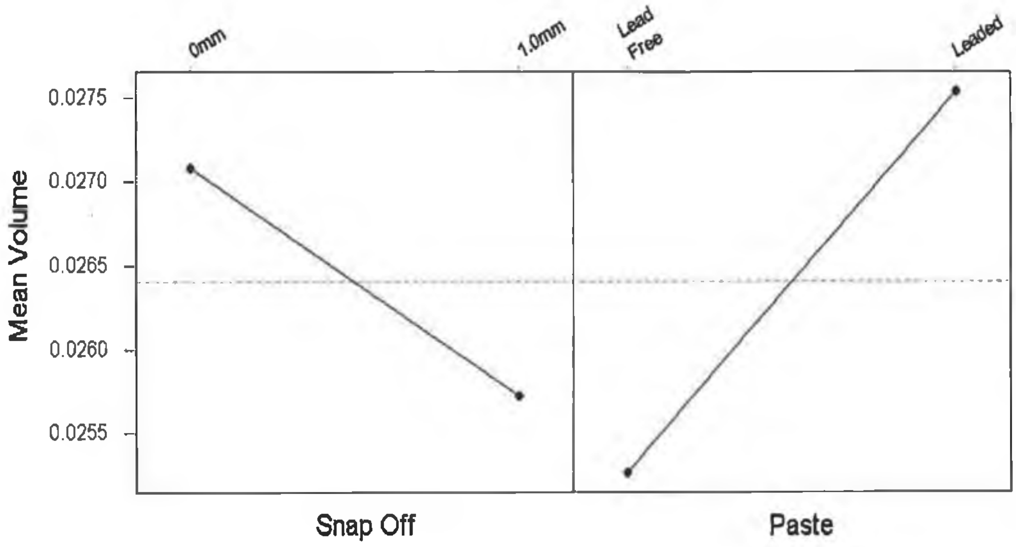

Figure 3.7 Main effects plot for mean solder paste volume

Figure 3.7 shows the main effects plot for the two factors, Snap off and Paste that were identified as statistically significant for the mean volume of the paste deposits. Tin-lead solder produces a paste deposit with greater volume than lead-free solder under identical operating conditions. A higher volume of deposit is also observed with a 0mm snap off.

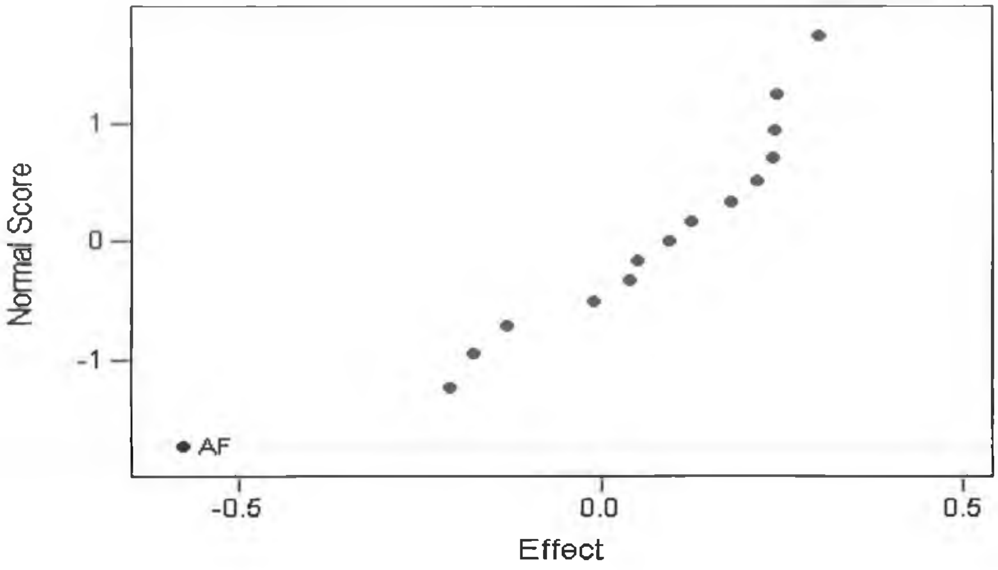

Figure 3.8 Normal probability plot of effects for solder paste volume variability (ln)

Figure 3.8 displays the normal probability plot of main effects for volume variability. The plot suggests there is an interaction between the A and F, i.e. the print speed and paste factors.

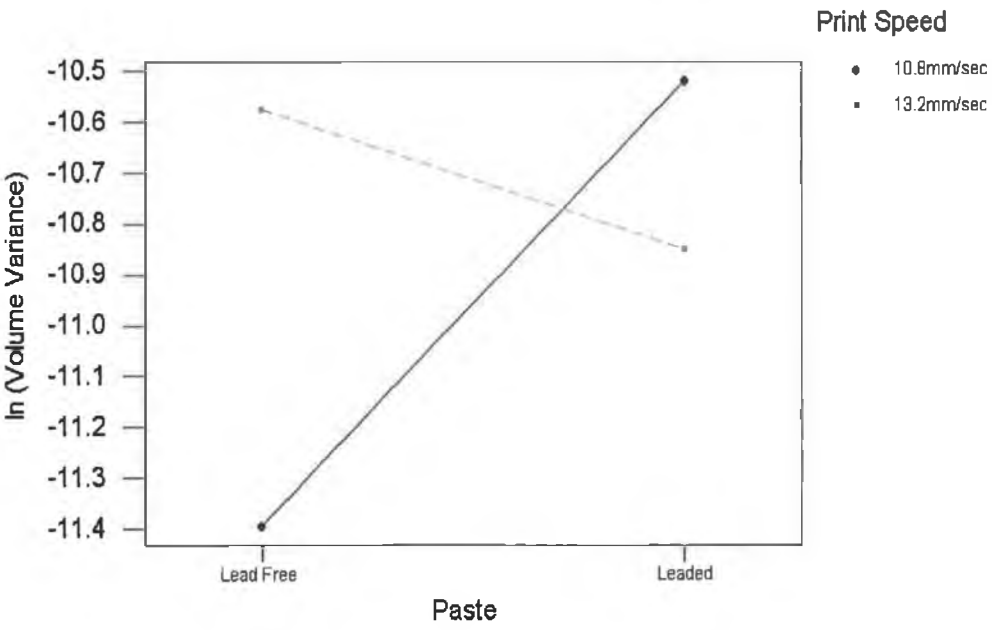

Figure 3.9 Interaction plot for the ln (Volume Variance)

Figure 3.9 shows the statistically significant interaction for the variation in volume of the paste deposit. Minimum variation in volume is observed when lead-free solder is used in association with a low print speed.

3.12.2 Solder Paste Volume Response Analysis – Lenth's Method

As with the solder paste height response the estimated effects and corresponding $|t_{PSE,i}|$ values were calculated and compared to tables of critical values of IER. The critical value again was 2.16 for an $\alpha = 5\%$ with 15 effects under consideration.

Term	**Effect**	$\left\|t_{PSE,i}\right\|$
A	0.00014	0.2333
B	- 0.00102	1.7000
C	- 0.000042	0.0700
D	- 0.00136	2.2667
E	0.00034	0.5667
F	0.00228	3.8000
AB	- 0.0007	1.1667
AC	0.00034	0.5667
AD	0.00006	0.1000
AE	- 0.00012	0.2000
AF	- 0.0011	1.8333
BD	0.00046	0.7667
BF	- 0.0013	2.1667
ABD	0.00046	0.7667
ABF	- 0.00022	0.3667

Table 3.5 Estimated effects for mean solder paste volume and corresponding $\left|t_{PSE,i}\right|$ values

From examination of the $\left|t_{PSE,i}\right|$ values in Table 3.5 it can be seen that factors D and F, i.e. snap off and paste are significant. The interaction of B and F is also seen as statistically significant. These factors and interactions all have $\left|t_{PSE,i}\right|$ values exceed the critical value of 2.16.

Term	**Effect**	$\left\|t_{PSE,i}\right\|$
A	0.24	0.8889
B	0.05	0.1852
C	- 0.18	0.6667
D	- 0.13	0.4815
E	0.24	0.8889
F	0.3	1.1111
AB	0.18	0.6667
AC	0.22	0.8148
AD	- 0.01	0.0370
AE	0.24	0.8889
AF	- 0.58	2.1481
BD	0.13	0.4815
BF	0.04	0.1481
ABD	0.1	0.3704
ABF	- 0.21	0.7778

Table 3.6 Estimated effects for solder paste volume variability (ln) and corresponding $\left|t_{PSE,i}\right|$ values

Table 3.6 shows the estimated effects and corresponding $\left|t_{PSE,i}\right|$ values for solder paste volume variability. The $\left|t_{PSE,i}\right|$ value for the interaction AF ie, the print speed and paste, is 2.148 and borders on the critical value of 2.16. This interaction was identified as significant in the corresponding normal probability plot shown in figure 3.6.

3.12.3 *Solder Paste Volume Response Conclusions*

Factor F, i.e. paste was found to be statistically significant for mean volume. It was shown by the main effects plot that tin-lead solder produces a paste deposit with greater volume than lead-free solder under identical operating conditions. Although statistically significant, this is not felt to be of much practical significance as the difference in mean volumes between lead-free and tin-lead is quite small. As a result it can be assumed that current SMT technology is capable of producing good quality solder paste deposits using lead-free solder paste. A higher volume of deposit is also observed with a 0mm snap off. It is therefore advisable to use a snap off of 0mm in such a solder stencil process. The experiment also shows that minimum volume variation was observed when lead-free solder is used in association with a low print speed. This result applies to the equipment used in this experiment. Again Lenth's method provide results that were similar to that observed when normal probability plots were used to identify effect significance.

3.13 Stencil Printing Experiment Conclusions

Results from the stencil printing experiment were analysed using two of the methods identified for analysis of unreplicated experimental designs. The first method used was Daniel's normal probability plot method. The factorial effects were calculated and plotted on normal probability graphs from which effect significance was estimated. The second method used was that developed by Lenth. Based on the results of the experiments, predictive equations were established to model the effect that the factors identified as significant have on the responses. In the case of the mean height of solder paste deposits, no factor was identified as significant. This implied that there was no significant difference between lead-free solder and tin-lead solder.

3.13.1 Solder Paste Height Variability Conclusions

The solder paste (Factor F) was identified as significant in the solder paste height variability experiment. The effects and ANOVA table for solder paste height variability together with the raw data is presented in Appendix A. The height variability predictive model was developed based on the significant factor Paste. The 0.264 term in the model equates to half the Paste effect. The constant value in the model represents the overall grand average of the solder paste height variability.

The model is presented below:

$$\hat{y} = -7.226 + [0.264]x_F$$

where:

$$y = \ln(s^2)$$

When the level of factor F is set to lead-free solder the predicted variance becomes:

$$\hat{s}^2_{Lead-Free} = 0.023mm$$

When the level of factor F is set to tin-lead the predicted variance becomes:

$$\hat{s}^2_{Tin-Lead} = 0.031mm$$

It is always useful to minimise variation in any process and this experiment demonstrated that lead-free solder produced less solder paste height variation than tin-lead solder at the same settings. Although the difference is statistically significant it is not felt to be of much practical significance.

3.13.2 Mean Solder Paste Volume Conclusions

Factors D, (snap off) and F, (paste) and the interaction BF were identified as significant in the mean solder paste volume experiment. The mean volume predictive model was developed based on these significant factors. The effects and ANOVA table for mean solder paste volume together with the raw data is presented in Appendix A.The predictive model is presented below:

$$\hat{y} = 0.0264 + [-0.00068]x_D + [0.0011]x_F + [-0.0065]x_{BF}$$

From examination of the main effects plot for snap off presented in Figure 3.7 section 3.12.1 it was observed that the highest volume was achieved at the low level setting of

0mm. The predicted responses when using lead-free and tin-lead solder paste, printed with a snap off of 0mm are:

$$\hat{y}_{Lead-Free} = 0.02594mm^3$$

$$\hat{y}_{Tin-Lead} = 0.02822mm^3$$

These values indicate a very small difference in predicted responses for mean solder paste volume when using lead-free paste and tin-lead paste. As with the solder paste height results, although the difference is statistically significant it is not felt to be of much practical significance.

3.13.3 Solder Paste Volume Variability Conclusions

An interaction between the print speed and solder paste factors (Factors A & F) was identified as significant in the solder paste volume variability experiment. The effects and ANOVA table for the solder paste volume variability together with the raw data is presented in Appendix A. The volume variability predictive model was developed based on the significant AF interaction.

The model is presented below:

$$\hat{y} = -10.83 + [-0.29]x_A x_F$$

where:

$$y = \ln(s^2)$$

From examination of the main effects plot in Figure 3.9 section 3.12.1 it can be seen that the least variation in solder paste volume is observed when lead-free solder is used in association with a low print speed.

The predicted volume variance when a low print speed is used with lead-free solder paste is:

$$\hat{s}_{Lead-Free} = 0.0038mm^3$$

The predicted volume variance when a low print speed is used with tin-lead solder paste is:

$$\hat{s}_{Tin-Lead} = 0.0067mm^3$$

This demonstrates that minimum variation was achieved when using lead-free solder paste.

3.14 Statistical Software

The statistical software used throughout the analysis in this study was Minitab®. Minitab® is a statistical software package used to manage and manipulate data and files, design experiments, analyse data and produce the required graphs amongst other things. The software can be used to help in many different quality improvement projects and includes functionality to help with quality tools such as statistical process control and design of experiments. Through out the course of this study it was used extensively to design and analyse the experimental designs. The analysis of data using Lenth's Method was completed using a standard Microsoft® Excel package.

3.15 Conclusion

This chapter documented the planning designing and conducting of an experimental design on the important SMT process of stencil printing. Due to the nature of the process an unreplicated fractional factorial was the experimental design of choice. The factors chosen for the experiment were based on similar experiments documented in the available literature and knowledge of the process used in the experiment. Four responses were selected. They were mean solder paste deposition height, mean solder paste deposition volume, solder paste deposition height variation and solder paste deposition volume variation. Daniels normal probability plots and Lenth's method were used to analyse the data and predictive models were developed. From examination of the predictive models it can be concluded that current stencil printing SMT technology is capable of producing good quality solder paste deposits using lead-free solder paste.

3.16 References

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CHAPTER 4

ASSESSMENT OF SOLDER JOINT QUALITY

4.0 Introduction

In this chapter the implications of introducing lead-free solder into the reflow soldering process are discussed. Part of the project scope was to investigate the effect of using lead-free solder in the reflow soldering process and to assess the quality of the resulting BGA solder joints. An objective of the work was to compare the quality of these solder joints to solder joints produced in the same process using tin-lead solder. During the course of the project it was discovered that no standard method exists to assess the quality of BGA solder joints. Solder joint quality is normally assessed using lengthy reliability tests that measure joint strength. It would be highly advantageous if a qualitative assessment method was available that could determine the joint quality. As a result a scoring method based on IPC guidelines was developed to evaluate solder joint quality quickly and inexpensively. This chapter details some of the existing methods for assessing solder joint quality and explains the mechanics of the scoring system developed to overcome the problem posed by the lack of a standard method for assessing BGA solder joint quality.

4.1 Reflow Soldering

In a typical SMT manufacturing process solder paste is printed onto PCBs after which the PCB is populated with electronic components using pick and place machines. The populated PCB is then reflow soldered using a reflow soldering oven to form the solder joint between the device and the PCB as illustrated in Figure 4.1. Hwang (1996) describes the various soldering methodologies used in industry.

A solder joint forms the electrical and mechanical connection between component and board. The quality of the solder joint is important as it will contribute to the proper operation of the product into which the PCB is placed.

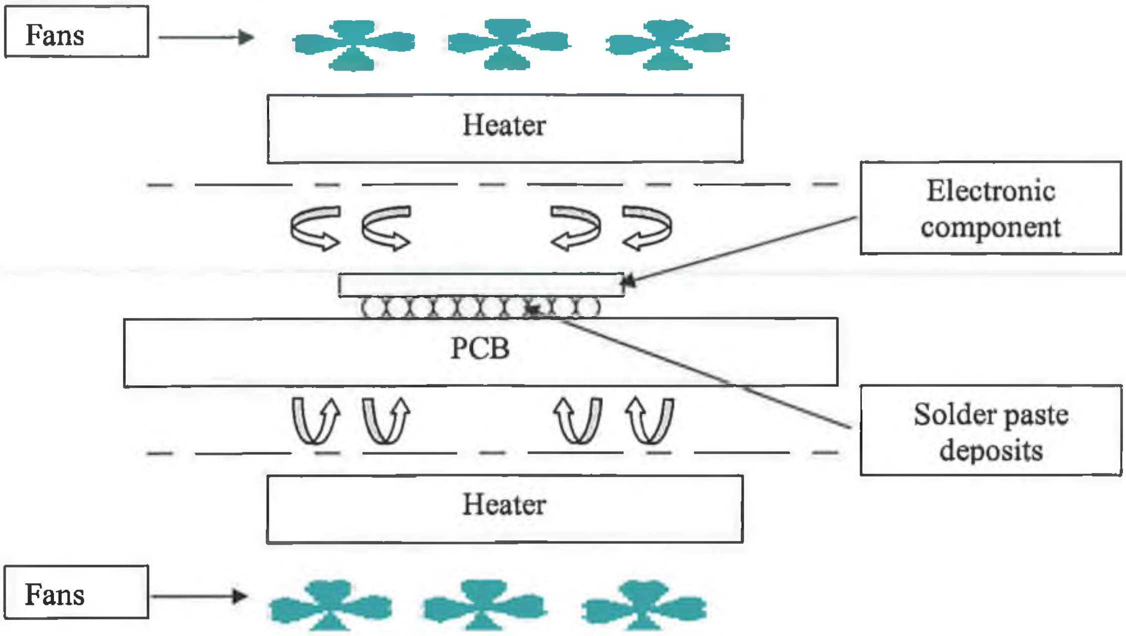

Figure 4.1 Convection reflow soldering diagram

4.2 Implications of Lead-Free Solder Introduction

One of the biggest challenges for electronic manufacturers converting their processes to lead-free will be the change in reflow temperatures. The melting temperature for tin-lead solder is 187°C. Most commercially available potential replacements to tin-led solders have melting temperatures higher than this. These temperatures range from 199°C up to 227°C as listed by Lee (1999) and Harrison *et al* (2001). The capability of existing equipment to deal with these temperatures needs to be tested. Although ovens designed specifically for lead-free reflow soldering are available, this may not be a feasible option for all electronics manufacturers. Board warpage, increased energy consumption and the impact of lead-free soldering on electronics packages as addressed by Yang *et al* (2001) are other areas that require consideration when implementing lead-free soldering.

The focus of this study is on the quality of solder joints produced by a SMT manufacturing line using lead-free solder compared to those produced using tin-lead solder. Existing test methods were researched and examined to establish a suitable method for assessing solder joint quality. Through a review of the literature it was found that solder joint quality is normally assessed using reliability tests as described in section 4.3.

4.3 Assessment Methods for Solder Joint Quality

There are various reliability test methods used to assess solder joint quality. Many of the methods are time consuming and require expensive specialised equipment. Authors such as Wang *et al* (2004), Ricky Lee *et al* (2002), and Tu *et al* (2001) describe test methods such as temperature cycling, power cycling, and cyclic bending mechanical tests that are used to measure solder joint strength. Table 4.1 presents a selection of methods used in various projects assembled from published work. The prevalence column in Table 4.1 relates to the occurrence of the individual test method in the literature reviewed. Temperature Cycling (TC) was the most common form of testing. Electrical resistance, force and strain were examples of the responses that were measured. The estimated time and cost associated with each method was also considered. For this project it was desirable to select a test method that wasn't very time consuming and was relatively inexpensive.

From this review it became apparent that no standard method existed for assessing BGA solder joint quality. It was determined by the project team that none of the available methods were suitable from both a practical and cost perspective. As a result a scoring method was devised based on the IPC-A-610 Rev. C standard. This standard defines what characteristics to look for in a good solder joint.

Prevalence	***Test Method***	***Response***
6	Temperature Cycling	Electrical Resistance
2	Three Point Bending	Electrical Resistance
2	Vibration Test	Electrical Resistance
2	Drop Test	Strain
1	Shear Test	Kilogram Force (Kfg)
1	Cyclic Bending	Electrical Continuity
1	Peel Test	Brittle Fracture
1	Four Point Twisting	Electrical Resistance
1	Liquid to Liquid Thermal Shock	Electrical Continuity
1	Temperature & Humidity Cycling	Electrical Continuity
1	Power Cycling Test	Electrical Resistance

Table 4.1 Reliability test methods for BGA solder joints

4.5 Scoring Method

Since no quantitative measure to evaluate BGA solder joint quality exists qualitative data was gathered through inspection of solder joint characteristics in accordance with the IPC standard. A fast and inexpensive method of assessing BGA solder joints was devised using visual evaluation of the solder joints and scoring the resulting inspection data.

The techniques used to evaluate the solder joints were x-ray and cross section analysis. Figures 4.2 and 4.3 show examples of both.

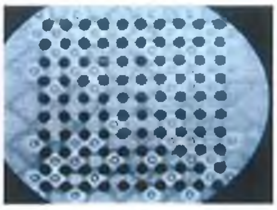

Figure 4.2 Solder joint x-ray

Figure 4.3 Solder joint cross section

X-Ray was used to examine for defects such as bridging, open joints, and solderballs. Cross sectioning was used to examine the joints in detail for solder joint formation, wetting, voids, and alignment. It was decided that a solder joint would be evaluated under the following categories and scored out of ten:

- Defects
- Solder Joint Formation
- Wetting
- Void Area
- Void Frequency
- Alignment

These categories were carefully chosen based on the guideline the IPC standard provided and knowledge of the process. A score of ten represented a bad joint and zero represented a good one. Each category was assigned a weight according to its importance as shown in

Table 4.2. For example an open joint is categorised as a defect that would cause failure of the component immediately, accordingly defects were assigned a high weighting. Inspection of the solder joints revealed that there were no defects on any PCB.

Category	***Category Nomenclature***	***Weight***	***Weight Nomenclature***
Defects	*D*	0.90	*a*
Solder Joint Formation	*JF*	0.80	*b*
Wetting	*W*	0.70	*c*
Void Area	*Va*	1.0	*x*
Void Frequency	*Vf*	1.0	*y*
Alignment	*A*	0.30	*z*

Table 4.2 Weighting values for BGA solder joint quality

Solder voids are cavities within a solder joint caused by gases that failed to escape from the joint before the solder solidified. There are two schools of thought on solder voids as explained by Lee (2002). On the one hand it is believed that voids reduce solder joint strength and affect electrical conductivity and on the other hand it is thought that voids can act as a crack terminator by slowing crack propagation in solder joints. Yunus *et al* (2004) describe how one of the primary functions of solder joints can be adversely affected by voids. Solder joints are required to conduct electrical signals and to allow this the electrical resistance should be as low as possible. The occurrence of large voids can reduce the cross sectional area of a solder joint and as a result increase resistance. Casey (1999) states that large voids can affect the mechanical and thermal properties of the solder joint which can reduce the mean time to failure.

The general consensus is that too much voiding is unacceptable. In this study the relationship between void area and void frequency was considered important. One large void occupying 50% of the solder joint was considered more serious than several smaller voids occupying the same area. Therefore, when void frequency (*Vf*) was greater than zero, the experimental run average weighted score denoted *Ws* was calculated as follows:

$$Ws = aD + \left(\frac{bJF + cW + \frac{xVa}{yVf} + zA}{n} \right)$$

When $Vf = 0$, Ws was calculated as:

$$Ws = aD + \left(\frac{bJF + cW + zA}{n} \right)$$

Table 4.2 explains the terms used in these equations. The upper case letters denote the score out of ten for the visual evaluation of the solder joints and the lower case letters represent the associated weight for the category scored. For example the category solder joint formation denoted *JF* is multiplied by its corresponding weight of 0.80 denoted *b*. Small *n* in the equation represents the number of solder balls assessed.

This method of scoring is best suited to processes with a low defect count. A high occurrence of defects in solder joints will cause immediate failure. Modern automated processes are less likely to exhibit high defect counts thus making this scoring method a suitable method of assessing solder joint quality from such processes.

4.6 Example of Scoring Method

Each cross sectioned BGA presented ten solder joints for scoring. Figure 4.4 shows an example of a cross sectioned area. Six solder joints are visible but the actual assessment was conducted on ten solder joints because the test BGA components were a 10x10 array.

Figure 4.4 Example of a BGA cross sectional area

One BGA was cross sectioned from each test board and scored against the criteria set out in section 4.5. An example of the scores for BGA test assembly number 1F is shown in Table 4.3. 1F signifies run one, lead-free assembly.

Part No.	Solder Joint No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
1F	1	0	3	2	3	1	1
	2	0	2	1	4	2	1
	3	0	1	1	0	0	1
	4	0	2	1	0	0	1
	5	0	3	1	5	2	1
	6	0	1	1	3	1	1
	7	0	2	1	2	1	1
	8	0	3	2	3	1	2
	9	0	2	1	0	0	1
	10	0	4	2	0	0	1

Table 4.3 Solder joint scores for run one, lead-free

A weighted score was calculated for each of the solder joints using the formulas in section 4.5.

Each of the scores from Table 4.3 were plugged into the formulas to give an average weighted score per BGA. The individual weighted scores for each solder joint and resulting average weighted score for assembly 1F is shown in Table 4.4. This was repeated for each assembly and the average weighted scores were analysed using experimental design techniques as explained in Chapter 5.

Joint 1	*Joint 2*	*Joint 3*	*Joint 4*	*Joint 5*	*Joint 6*	*Joint 7*	*Joint 8*	*Joint 9*	*Joint 10*	***Average Weighted Score***
0.71	0.46	0.18	0.26	0.59	0.48	0.46	0.74	0.26	0.49	**4.63**

Table 4.4 Individual solder joint scores and average weighted score for run one, lead - free

The calculation of the weighted score for joint 1 is presented below and is based on the scores awarded to joint 1 as presented in Table 4.3.

$$Ws = aD + \left(\frac{bJF + cW + \dfrac{xVa}{yVf} + zA}{n} \right)$$

$$Ws_{Joint1} = 0.9(0) + \left(\frac{0.8(3) + 0.7(2) + \left(\dfrac{3}{1}\right) + 0.3(1)}{10} \right)$$

$$Ws_{Joint1} = 0.71$$

4.7 Conclusion

Reflow soldering is another important step in the SMT process. This chapter examines the implications of introducing lead-free solder into the process. The most important difference between and tin-lead and lead-free reflow soldering process is the elevated temperatures required for lead-free solder. An objective of this research was to compare the quality of solder joints made using lead-free solder to those made using tin-lead solder. A review of testing methods was conducted to identify a suitable test to compare the solder joints for this study. No suitable test was found so a scoring method based on IPC standards was developed to test the quality of the lead-free and tin-lead solder joints. The test method is based on x-ray and cross section analysis and provides a quick and inexpensive way to assess solder joint quality.

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CHAPTER 5

EXPERIMENTATION OF REFLOW SOLDERING PROCESS

5.0 Introduction

This chapter details the set-up of an experimental design conducted on a SMT reflow soldering process using tin-lead and lead-free solder pastes. The experiment was carried out to determine if the quality of a solder joint produced using lead-free solder was comparable to the quality of a solder joint manufactured under similar conditions using tin-lead solder. The chapter describes the planning and set-up of the experimental design. The analysis technique used to assess the experimental data is also presented and the results are discussed.

5.1 Reflow Soldering

Reflow soldering is the process of heating, cooling and solidifying solder paste to form the solder joint between mounted components and PCBs. There are several reflow methodologies as described by Hwang (1996). Convection reflow soldering was the method employed in this study. An advantage of convection reflow is the number of heating zones in a convection oven offers flexibility in reflow temperature profiling. Convection reflow also provides a slow heat transfer to the components and as a result this will minimise component cracking. Key process parameters that affect the quality of solder joints include:

- Preheating temperature
- Preheating time
- Peak temperature
- Dwell time at peak temperature
- Cooling rate

In order to achieve good solder joints, reflow temperature profiles must be developed for the particular solder paste and reflow oven being used. A reflow temperature profile represents the relationship of temperature and time during the reflow process. According to Lee (2002) many component manufacturers recommend a temperature rise of 2° to 4° C per second as anything steeper could result in component cracking or solder paste slump. Either one of these two occurring could cause a board failure.

In a study carried out on the impact of lead-free solders on electronics components, Yang *et al* (2001) recommended that either the reflow conditions should change or a new set of materials should be developed for electronic components. Salem *et al* (2004) discovered that the peak temperature was the most significant factor in their reflow profile study of a Sn-Ag-Cu solder. Testing is therefore necessary to get the correct reflow temperature profile and to avoid any loss of component integrity.

5.1.1 Reflow Temperature Profiling

A number of studies have been conducted on reflow soldering processes using lead-free solders. Harrison *et al* (2001), Collier *et al* (2002) and Salem *et al* (2004) have all published work on the topic. Harrison *et al* (2001) selected a number of lead-free alloys and tested them against certain characteristics to determine and recommend a lead-free alloy of choice to be used in industry. The results reported that a 96Sn3.8Ag0.7Cu alloy was the best all round solution for lead-free reflow soldering. Wetting performance, solderability, microstructure and other mechanical properties such as elasticity were assessed. Some of the inspection techniques included x-ray and cross sectional analysis.

Typical factors used in experimental designs on reflow soldering processes included the temperatures involved in the reflow profile. In this study a Datapac 9000 profiling kit was used to develop a reflow temperature profile that closely mirrored the temperature profile recommended for the solder paste used. Typically, the solder paste manufacturer would recommend such a reflow profile.

A test circuit board which mimicked the boards to be used in the experimental design was built and thermocouples were soldered under the on-board BGA components. A data logger was used to record the temperature profile experienced by the board as it passed through the reflow oven. The reflow oven used was 5-zone Vitronics Isotherm 500S convection reflow oven as shown in Figure 5.1. The recommended reflow profile for the 95.5Sn3.8Ag0.7Cu solder paste is shown in Figure 5.2. The test vehicle was the same as used in the stencil printing profile as is shown in Figure 3.2 in Chapter 3. Each test board was printed with solder paste using the optimum settings from the stencil printing experiment. Eight BGA were placed in board positions 1-4 and 9-12 on each test board using an OKI Craft BGA Rework and Placement Station.

Figure 5.1 Vitronics Isotherm 500S convection reflow oven

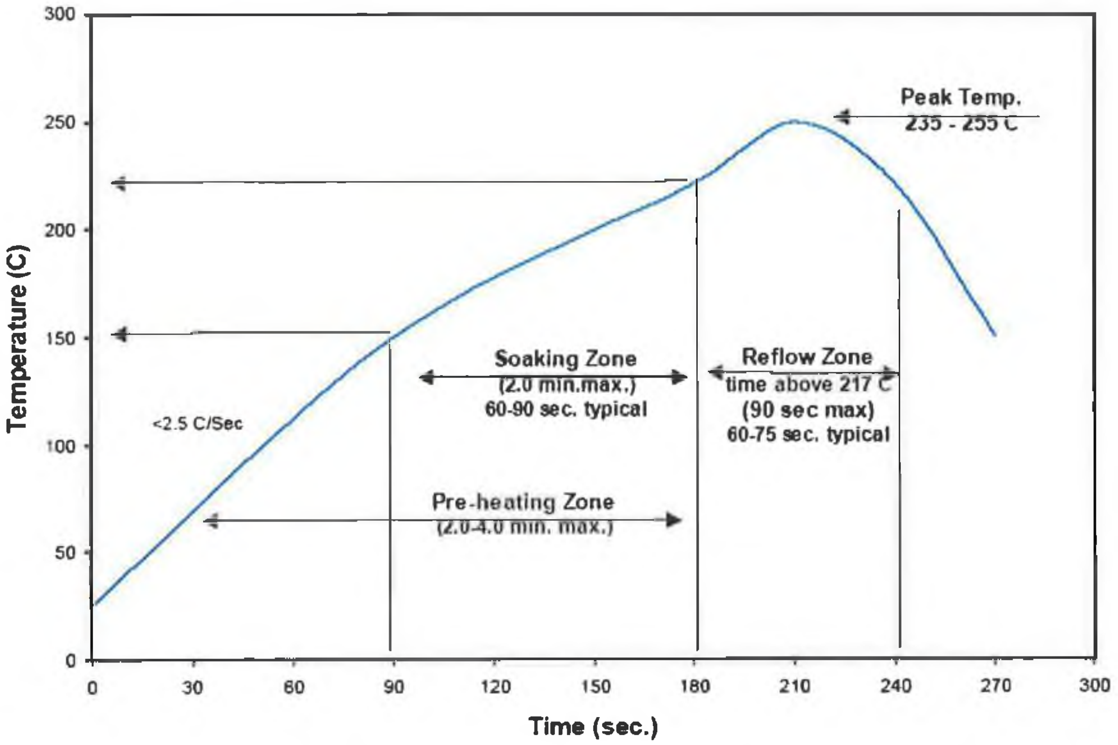

Figure 5.2 Recommended reflow profile for 95.5Sn3.8Ag0.7Cu solder paste

5.2 Factors and Levels for Reflow Soldering Experimental Design

Factors and levels for the reflow soldering experimental design were chosen based on knowledge of the process, a review of similar work already carried out such as Gagne *et al* (1996) and Skidmore and Walters (2000) and the reflow oven used in the chosen manufacturing process. Six factors were selected. These related to the five temperature zones in the reflow oven and the speed of the oven conveyor belt. The five temperature zones are listed below:

- Preheat temperature 1 (Zone 1)
- Preheat temperature 2 (Zone 2)
- Soak temperature (Zone 3)
- Reflow temperature 1 (Zone 4)
- Reflow temperature 2 (Zone 5)

In relation to the reflow temperature profile shown in Figure 5.2 the first three of these five temperatures relate to the pre-heating and soaking zones. The last two temperatures relate to the reflow zone in the temperature profile. Experiments involving these factors were conducted on both the lead-free and tin-lead solder pastes. The response data gained from these experiments was combined and then analysed using nested design techniques. A new factor called solder paste was introduced to the experiment in the analysis. Due to the different melting temperatures required for tin-lead and lead-free solders the levels of the temperature factor are similar but not identical as shown in Table 4.3. This arrangement is considered nested or hierarchical, the levels of the temperature zones are nested under the paste factor.

<table>
<tr><th colspan="3">Tin – Lead Factor Levels</th></tr>
<tr><th>Factor</th><th>-</th><th>+</th></tr>
<tr><td>Conveyor Speed</td><td>12 inches/min</td><td>14 inches/min</td></tr>
<tr><td>Preheat temperature 1</td><td>160°C</td><td>170°C</td></tr>
<tr><td>Preheat temperature 2</td><td>175°C</td><td>185°C</td></tr>
<tr><td>Soak temperature</td><td>190°C</td><td>200°C</td></tr>
<tr><td>Reflow temperature 1</td><td>220°C</td><td>230°C</td></tr>
<tr><td>Reflow temperature 2</td><td>270°C</td><td>280°C</td></tr>
</table>

<table>
<tr><th colspan="3">Lead Free Factor Levels</th></tr>
<tr><th>Factor</th><th>-</th><th>+</th></tr>
<tr><td>Conveyor Speed</td><td>12 inches/min</td><td>14 inches/min</td></tr>
<tr><td>Preheat temperature 1</td><td>170°C</td><td>180°C</td></tr>
<tr><td>Preheat temperature 2</td><td>210°C</td><td>220°C</td></tr>
<tr><td>Soak temperature</td><td>230°C</td><td>240°C</td></tr>
<tr><td>Reflow temperature 1</td><td>245°C</td><td>265°C</td></tr>
<tr><td>Reflow temperature 2</td><td>280°C</td><td>315°C</td></tr>
</table>

Table 5.1 Factor levels for reflow soldering of tin–lead and lead–free solder pastes

5.2.1 Nested Experimental Designs

Nested designs occur when the levels of one factor are similar but not identical for different levels of another factor. In the reflow soldering experiment the temperature factors are similar but not quite the same for tin-lead and lead-free solder. The preheat temperature 1, preheat temperature 2, soak temperature, reflow temperature 1 and reflow temperature 2 are all nested under the solder paste factor which has two levels, tin-lead solder paste and lead-free solder paste as illustrated in Figure 5.3. The temperature factors are said to be nested under the paste factor.

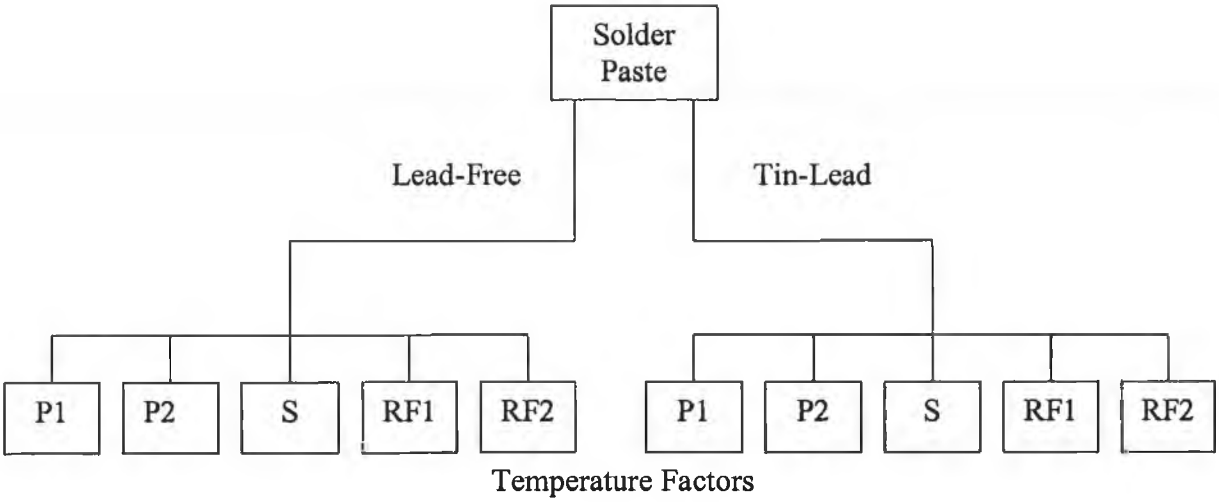

Figure 5.3 Nested structure of paste and temperature factors

Smith and Beverly (1981) explain how nesting can occur and suggest techniques to analyse nested designs. Nelson (1995a) and (1995b) describes a multistage system similar to Figure 5.3 and states that nested designs are needed for estimating variance in these systems. Jin and Guo (2003) use nested techniques to analyse a batch manufacturing as does Montgomery (2001).

5.3 Experimental Design

A 2_{IV}^{6-2} experimental design was conducted on the process for both tin–lead and lead–free solder. This implied a total of thirty-two experimental runs. The levels of the factors for the tin–lead and lead–free experiments are displayed in Table 5.1. The nested relationship between solder paste and temperatures can be observed by examining the temperature requirements for both solder paste types.

5.4 Experimental Design Analysis

The average weighted score was the response analysed for effect significance. Average weighted scores for the thirty-two experimental runs were calculated using the equations developed in chapter four and the scores that were assigned to the solder joints after they were assessed against several quality criteria. Appendix B shows the raw data including the average weighted score for each of the thirty-two experimental runs. The resulting ANOVA table from the analysis is presented below in Table 5.2

Source	DF	SS	MS	F	P
Belt Speed	1	5.6928	5.6928	9.84	0.006
Paste	1	1.5945	1.5945	2.76	0.114
PreHeat 1(Paste)	2	1.9170	0.9585	1.66	0.218
PreHeat 2(Paste)	2	0.5057	0.2529	0.44	0.653
Soak(Paste)	2	0.0311	0.0155	0.03	0.974
Reflow 1(Paste)	2	2.4218	1.2109	2.09	0.152
Reflow 2(Paste)	2	2.3702	1.1851	2.05	0.158
Belt Speed*Paste	1	1.6694	1.6694	2.89	0.107
Error	18	10.4104	0.5784		
Total	31	26.6130			

Table 5.2 Nested ANOVA table for reflow soldering experiment

Examination of the *p* values reflects that factor A i.e. belt speed, is significant at the 5% level. A review of the main effects plot shown in Figure 5.3 indicates that the best response, i.e. the lowest weighted score, is achieved at the higher conveyor speed of 14 inches per second. The analysis also indicates that the solder paste and the temperature factors were not statistically significant. This implies that the lead-free solder paste and the associated higher temperatures has a similar joint quality profile to that of tin-lead solder.

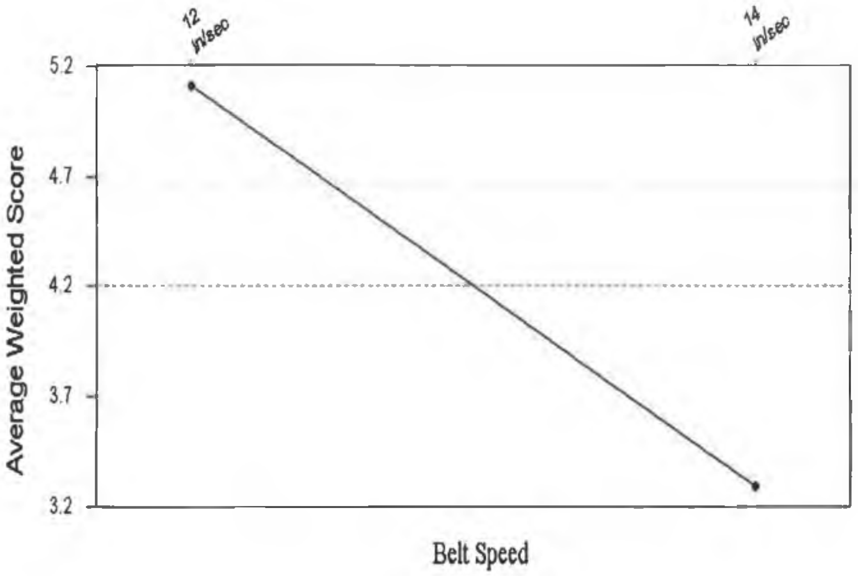

Figure 5.4 Main effects plot for conveyor belt speed

5.5 Validation of Results (Residual Analysis)

The residuals were analysed to confirm the ANOVA assumptions were not violated. It was assumed that errors were normally and independently distributed with equal variance and mean of zero. Examination of residuals verifies whether these assumptions hold true and provides model validation.

Typically the tests used to confirm the normality distribution assumption are a histogram plot or a normal probability plot of the residuals. A histogram should look like a sample from a normal distribution centred on zero. Ideally there should be a large number of observations to properly observe a normal distribution. A slight deviation from a normal distribution when using a small sample does not imply a violation of the assumptions. An effective test of normality is a normal probability plot of the residuals. If the residuals are normally distributed this plot will resemble a straight line.

The independence assumption can be verified by plotting the residuals in the order the data was collected. This plot should not display any runs of positive or negative values. The assumption of constant variance is verified by plotting the residuals versus the fitted or predicted values. If the plot displays a structureless pattern this assumption is satisfied.

Figure 5.4 displays the residual analysis for the reflow soldering experiment. Examination of the residual plots shows that no assumptions were violated.

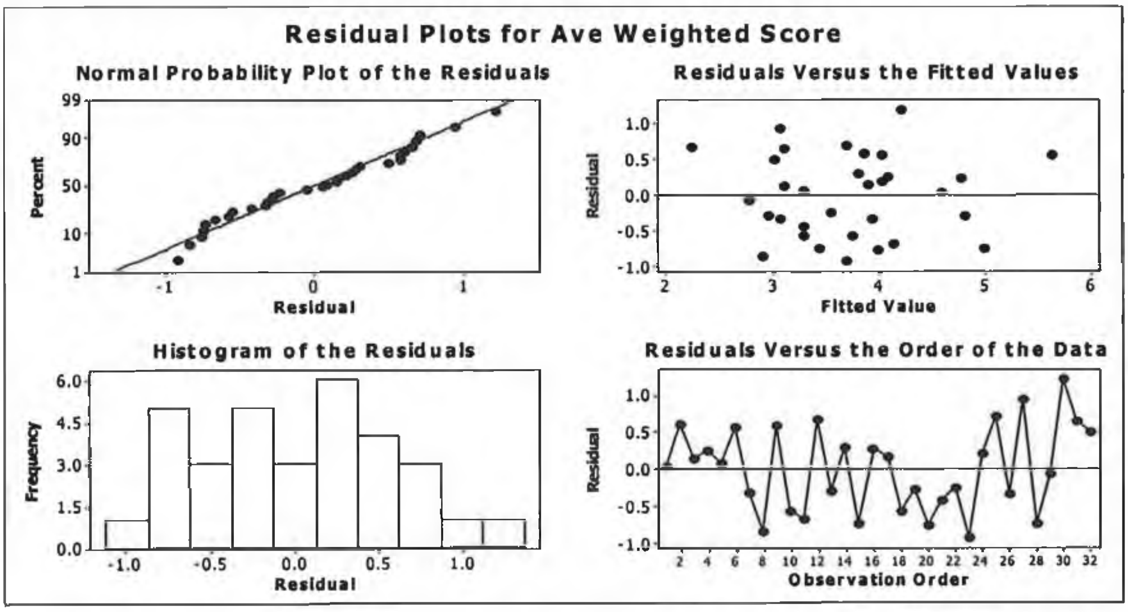

Figure 5.5 Residual analysis for the reflow soldering experiment

5.6 Reflow Soldering Experiment Conclusions

The average weighted scores for the thirty-two experimental runs were analysed for effect significance. The resulting ANOVA table is presented in Table 5.2 in section 5.4. Examination of the *p* values reflects that factor A i.e. belt speed, is significant at the 5% level. A review of the main effects plot presented in Figure 5.4, section 5.4 indicates that the best response, i.e. the lowest weighted score, is achieved at the higher conveyor speed of 14 inches per second. One possible reason for this is the solder joints were exposed to excessive heat while passing through the reflow oven at the slower speed.

The analysis also indicated that the solder paste and the temperature factors were not statistically significant. This implies that the lead-free solder paste and the associated higher temperatures has a similar joint quality profile to that of tin-lead solder.

The raw data and the calculated average weighted score for each of the thirty-two experimental runs are presented in Appendix B. The predicted average weight score is presented below:

$$\hat{y} = 3.71 + [0.9]x_A$$

The constant value in the model represents the overall grand average of the average weighted scores and the second term represents half the Belt Speed effect.

5.7 Conclusion

This chapter described the planning and set-up of an experimental design on a reflow soldering using lead-free and tin-lead solder. The resulting data was analysed using nested design techniques because the temperature factors are similar but not quite the same for tin-lead and lead-free solder exhibiting a nested relationship. An objective of the chapter was to determine if the quality of a solder joint produced using lead-free solder was comparable to the quality of a solder joint manufactured under similar conditions using tin-lead solder. It can be concluded from the analysis of the data that it is possible to produce solder joints of similar quality.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.0 Introduction

In this chapter conclusions are drawn from the results of the stencil printing and reflow soldering experiments and recommendations based on these conclusions are made.

6.1 Conclusions Summary

The use of lead-free solder in electronic manufacturing will become a reality for European manufacturers before July 2006. This research presents a comparative study of tin-lead solder and lead-free solder in the stencil printing process and the reflow soldering process. The key process indicators examined in the stencil printing experiment were solder paste height & height variation and solder paste volume & volume variation. The analysis of the experiments highlighted the following:

- Solder paste was statistically significant for solder paste height variance with lead-free paste producing less variation than tin-lead.
- Snap off and solder paste was statistically significant for mean solder paste volume. The experiment showed that when snap off was set at 0mm and the paste type was tin-lead solder, the volume was higher. However the predictive models demonstrated that although statistically significant it is not of much practical significance as the difference in mean volumes between lead-free and tin-lead solder paste is quite small.

- An interaction between print speed and paste was statistically significant for volume variance. Predictive models demonstrated that minimum variation was achieved when using lead-free solder paste.

Since no method of rating BGA solder joints quality was available, a scoring method was developed against accepted industry standards to assess the quality of the solder joints produced in the reflow soldering experiment. The analysis of this experiment indicated that:

- Conveyer belt speed had a significant effect on the average weighted score of solder joint quality and the best response is achieved at the higher speed of 14 inches per second.
- Tin-lead and lead-free solder joints produced solder joints of comparable quality indicating that solder paste type was not significant in the experiment.

The outcomes of the experiments conducted in this study demonstrate that it is possible to produce results using lead-free solder with current equipment that are comparable to existing tin-lead solders. It can be concluded that it is possible to use the currently available SMT equipment to produce a product using lead-free paste, which gives good solder joints of equal standard to that of tin-lead.

6.3 Recommendations

The testing and experimentation conducted during this research was carried out on specific SMT process machinery using a specific lead-free solder alloy. When introducing lead-free solder into an SMT process it is important that the manufacturer tests and experiments with their equipment using their chosen lead-free solder alloy. The methods and procedures employed in this research can be adopted to test existing process machinery to investigate the suitability of a number of lead-free alloys. The results of the experiments in this research demonstrated the suitability of the methods selected.

Appendix A
Stencil Printing Experiment Raw Data

Mean Solder Paste Height Data

StdOrder	RunOrder	Print Speed	Squeegee Pressure	Separation Speed	Snap Off	Cleaning Interval	Paste																										Average Height
5	1	10.8mm/sec	3.6kg	15%	0mm	Every 10 Boards	Leaded	0.216	0.184	0.212	0.233	0.199	0.231	0.198	0.192	0.184	0.242	0.181	0.205	0.199	0.189	0.231	0.197	0.21	0.19	0.263	0.277	0.194	0.184	0.181	0.232	0.227	0.21004
11	9	10.8mm/sec	4.4kg	10%	1.0mm	Every 10 Boards	Lead Free	0.197	0.177	0.195	0.198	0.228	0.202	0.17	0.214	0.173	0.21	0.215	0.171	0.195	0.232	0.219	0.193	0.165	0.212	0.177	0.169	0.198	0.178	0.183	0.188	0.166	0.193
6	2	13.2mm/sec	3.6kg	15%	0mm	Every 5 Boards	Leaded	0.221	0.208	0.19	0.216	0.211	0.204	0.183	0.223	0.202	0.237	0.228	0.207	0.216	0.231	0.232	0.199	0.172	0.253	0.177	0.26	0.19	0.187	0.187	0.169	0.27	0.21092
13	10	10.8mm/sec	3.6kg	15%	1.0mm	Every 10 Boards	Lead Free	0.207	0.204	0.22	0.214	0.224	0.196	0.2	0.212	0.21	0.23	0.235	0.198	0.219	0.197	0.177	0.222	0.198	0.212	0.199	0.174	0.213	0.214	0.202	0.214	0.163	0.20616
9	3	10.8mm/sec	3.6kg	10%	1.0mm	Every 5 Boards	Leaded	0.222	0.215	0.208	0.176	0.182	0.192	0.224	0.205	0.222	0.169	0.241	0.182	0.282	0.227	0.147	0.187	0.193	0.184	0.176	0.227	0.168	0.174	0.182	0.185	0.234	0.20016
16	4	13.2mm/sec	4.4kg	15%	1.0mm	Every 10 Boards	Leaded	0.123	0.203	0.193	0.173	0.221	0.21	0.244	0.134	0.215	0.213	0.216	0.227	0.14	0.24	0.198	0.212	0.231	0.153	0.191	0.16	0.196	0.209	0.162	0.208	0.145	0.19268
14	11	13.2mm/sec	3.6kg	15%	1.0mm	Every 5 Boards	Lead Free	0.214	0.2	0.198	0.203	0.19	0.178	0.168	0.188	0.212	0.192	0.194	0.194	0.195	0.222	0.25	0.199	0.199	0.208	0.185	0.147	0.206	0.194	0.206	0.181	0.195	0.19672
3	5	10.8mm/sec	4.4kg	10%	0mm	Every 10 Boards	Leaded	0.267	0.238	0.198	0.165	0.248	0.28	0.241	0.174	0.137	0.21	0.24	0.255	0.139	0.244	0.201	0.221	0.201	0.259	0.204	0.18	0.192	0.234	0.224	0.2	0.146	0.21192
7	12	10.8mm/sec	4.4kg	15%	0mm	Every 5 Boards	Lead Free	0.2	0.185	0.199	0.199	0.186	0.185	0.187	0.158	0.216	0.202	0.214	0.241	0.177	0.209	0.172	0.188	0.218	0.154	0.182	0.2	0.205	0.193	0.183	0.198	0.151	0.19208
15	6	10.8mm/sec	4.4kg	15%	1.0mm	Every 5 Boards	Leaded	0.23	0.224	0.136	0.219	0.197	0.219	0.237	0.158	0.176	0.165	0.225	0.258	0.154	0.204	0.19	0.211	0.197	0.206	0.208	0.17	0.208	0.242	0.29	0.228	0.186	0.20552
2	13	13.2mm/sec	3.6kg	10%	0mm	Every 10 Boards	Lead Free	0.209	0.191	0.243	0.176	0.219	0.173	0.219	0.234	0.179	0.192	0.191	0.222	0.285	0.191	0.244	0.214	0.17	0.215	0.162	0.18	0.18	0.167	0.209	0.182	0.217	0.20258
10	7	13.2mm/sec	3.6kg	10%	1.0mm	Every 10 Boards	Leaded	0.239	0.193	0.212	0.199	0.181	0.201	0.207	0.159	0.215	0.184	0.226	0.204	0.177	0.272	0.187	0.217	0.187	0.222	0.208	0.167	0.253	0.214	0.259	0.218	0.18	0.20724
1	14	10.8mm/sec	3.6kg	10%	0mm	Every 5 Boards	Lead Free	0.176	0.204	0.234	0.177	0.233	0.175	0.194	0.194	0.169	0.22	0.187	0.196	0.207	0.244	0.199	0.187	0.222	0.203	0.168	0.14	0.219	0.194	0.231	0.192	0.15	0.19656
8	15	13.2mm/sec	4.4kg	15%	0mm	Every 10 Boards	Lead Free	0.158	0.195	0.218	0.208	0.201	0.201	0.178	0.291	0.203	0.273	0.19	0.214	0.209	0.172	0.27	0.207	0.203	0.219	0.211	0.173	0.182	0.207	0.213	0.19	0.15	0.20544
4	8	13.2mm/sec	4.4kg	10%	0mm	Every 5 Boards	Leaded	0.205	0.194	0.277	0.206	0.165	0.226	0.212	0.24	0.216	0.174	0.23	0.204	0.239	0.211	0.149	0.21	0.219	0.256	0.21	0.159	0.211	0.24	0.269	0.216	0.16	0.21192
12	16	13.2mm/sec	4.4kg	10%	1.0mm	Every 5 Boards	Lead Free	0.196	0.221	0.223	0.215	0.227	0.206	0.209	0.243	0.18	0.245	0.218	0.22	0.224	0.193	0.282	0.216	0.211	0.183	0.18	0.214	0.202	0.187	0.181	0.153	0.207	0.20944

Solder Paste Height Variance Data

StdOrder	RunOrder	Print Speed	Squeegee Pressure	Separation Speed	Snap Off	Cleaning Interval	Paste																										Standard Deviation	Variance	Ln Variance
5	1	10.8mm/sec	3.6kg	15%	0mm	Every 10 Boards	Leaded	0.216	0.184	0.212	0.233	0.199	0.231	0.198	0.192	0.184	0.242	0.181	0.205	0.199	0.189	0.231	0.197	0.21	0.19	0.263	0.277	0.194	0.184	0.181	0.232	0.227	0.0260264	0.000677	-7.29729
11	9	10.8mm/sec	4.4kg	10%	1.0mm	Every 10 Boards	Lead Free	0.197	0.177	0.195	0.198	0.228	0.202	0.17	0.214	0.173	0.21	0.215	0.171	0.195	0.232	0.219	0.193	0.165	0.212	0.177	0.169	0.198	0.178	0.183	0.188	0.166	0.0199123	0.000397	-7.83283
6	2	13.2mm/sec	3.6kg	15%	0mm	Every 5 Boards	Leaded	0.221	0.208	0.19	0.216	0.211	0.204	0.183	0.223	0.202	0.237	0.228	0.207	0.216	0.231	0.232	0.199	0.172	0.253	0.177	0.26	0.19	0.187	0.187	0.169	0.27	0.0268513	0.000721	-7.23488
13	10	10.8mm/sec	3.6kg	15%	1.0mm	Every 10 Boards	Lead Free	0.207	0.204	0.22	0.214	0.224	0.196	0.2	0.212	0.21	0.23	0.235	0.198	0.219	0.197	0.177	0.222	0.198	0.212	0.199	0.174	0.213	0.214	0.202	0.214	0.163	0.0168565	0.000284	-8.16604
9	3	10.8mm/sec	3.6kg	10%	1.0mm	Every 5 Boards	Leaded	0.222	0.215	0.208	0.176	0.182	0.192	0.224	0.205	0.222	0.169	0.241	0.182	0.282	0.227	0.147	0.187	0.193	0.184	0.176	0.227	0.168	0.174	0.182	0.185	0.234	0.0297443	0.000885	-7.03024
16	4	13.2mm/sec	4.4kg	15%	1.0mm	Every 10 Boards	Leaded	0.123	0.203	0.193	0.173	0.221	0.21	0.244	0.134	0.215	0.213	0.216	0.227	0.14	0.24	0.198	0.212	0.231	0.153	0.191	0.16	0.196	0.209	0.162	0.208	0.145	0.0344102	0.001184	-6.73881
14	11	13.2mm/sec	3.6kg	15%	1.0mm	Every 5 Boards	Lead Free	0.214	0.2	0.198	0.203	0.19	0.178	0.168	0.188	0.212	0.192	0.194	0.194	0.195	0.222	0.25	0.199	0.199	0.208	0.185	0.147	0.206	0.194	0.206	0.181	0.195	0.0189022	0.000357	-7.93695
3	5	10.8mm/sec	4.4kg	10%	0mm	Every 10 Boards	Leaded	0.267	0.238	0.198	0.165	0.248	0.28	0.241	0.174	0.137	0.21	0.24	0.255	0.139	0.244	0.201	0.221	0.201	0.259	0.204	0.18	0.192	0.234	0.224	0.2	0.146	0.0398298	0.001586	-6.44628
7	12	10.8mm/sec	4.4kg	15%	0mm	Every 5 Boards	Lead Free	0.2	0.185	0.199	0.199	0.186	0.185	0.187	0.158	0.216	0.202	0.214	0.241	0.177	0.209	0.172	0.188	0.218	0.154	0.182	0.2	0.205	0.193	0.183	0.198	0.151	0.0206356	0.000426	-7.76143
15	6	10.8mm/sec	4.4kg	15%	1.0mm	Every 5 Boards	Leaded	0.23	0.224	0.136	0.219	0.197	0.219	0.237	0.158	0.176	0.165	0.225	0.258	0.154	0.204	0.19	0.211	0.197	0.206	0.208	0.17	0.208	0.242	0.29	0.228	0.186	0.0346014	0.001197	-6.72772
2	13	13.2mm/sec	3.6kg	10%	0mm	Every 10 Boards	Lead Free	0.209	0.191	0.243	0.176	0.219	0.173	0.219	0.234	0.179	0.192	0.191	0.222	0.285	0.191	0.244	0.214	0.17	0.215	0.162	0.18	0.18	0.167	0.209	0.182	0.217	0.0293614	0.000862	-7.05615
10	7	13.2mm/sec	3.6kg	10%	1.0mm	Every 10 Boards	Leaded	0.239	0.193	0.212	0.199	0.181	0.201	0.207	0.159	0.215	0.184	0.226	0.204	0.177	0.272	0.187	0.217	0.187	0.222	0.208	0.167	0.253	0.214	0.259	0.218	0.18	0.0280302	0.000786	-7.14895
1	14	10.8mm/sec	3.6kg	10%	0mm	Every 5 Boards	Lead Free	0.176	0.204	0.234	0.177	0.233	0.175	0.194	0.194	0.169	0.22	0.187	0.196	0.207	0.244	0.198	0.187	0.222	0.203	0.168	0.14	0.219	0.194	0.231	0.192	0.15	0.0262283	0.000688	-7.28183
8	15	13.2mm/sec	4.4kg	15%	0mm	Every 10 Boards	Lead Free	0.158	0.195	0.218	0.208	0.201	0.201	0.178	0.291	0.203	0.273	0.19	0.214	0.209	0.172	0.27	0.207	0.203	0.219	0.211	0.173	0.182	0.207	0.213	0.19	0.15	0.032923	0.001084	-6.82717
4	8	13.2mm/sec	4.4kg	10%	0mm	Every 5 Boards	Leaded	0.205	0.194	0.277	0.206	0.165	0.226	0.212	0.24	0.216	0.174	0.23	0.204	0.239	0.211	0.149	0.21	0.219	0.256	0.21	0.159	0.211	0.24	0.269	0.216	0.16	0.0328671	0.00108	-6.83057
12	16	13.2mm/sec	4.4kg	10%	1.0mm	Every 5 Boards	Lead Free	0.196	0.221	0.223	0.215	0.227	0.206	0.209	0.243	0.18	0.245	0.218	0.22	0.224	0.193	0.282	0.216	0.211	0.183	0.18	0.214	0.202	0.187	0.181	0.153	0.207	0.0260049	0.000676	-7.29894

Appendix A
Stencil Printing Experiment Raw Data

Mean Solder Paste Volume Data

RunOrder	Print Speed	Squeegee Pressure	Separation Speed	Snap Off	Cleaning Interval	Paste																										Average Volume
1	10.8mm/sec	3.6kg	15%	0mm	Every 10 Boards	Leaded	0.026	0.024	0.026	0.03	0.03	0.027	0.029	0.029	0.026	0.036	0.022	0.024	0.031	0.027	0.033	0.029	0.029	0.021	0.039	0.038	0.031	0.027	0.029	0.038	0.031	0.02928
9	10.8mm/sec	4.4kg	10%	1.0mm	Every 10 Boards	Lead Free	0.023	0.019	0.023	0.026	0.026	0.022	0.022	0.028	0.023	0.029	0.028	0.023	0.029	0.033	0.03	0.024	0.022	0.029	0.024	0.022	0.025	0.023	0.024	0.023	0.023	0.02492
2	13.2mm/sec	3.6kg	15%	0mm	Every 5 Boards	Leaded	0.034	0.026	0.028	0.028	0.024	0.03	0.025	0.032	0.031	0.026	0.03	0.03	0.035	0.031	0.033	0.032	0.023	0.039	0.025	0.037	0.027	0.027	0.028	0.025	0.035	0.02964
10	10.8mm/sec	3.6kg	15%	1.0mm	Every 10 Boards	Lead Free	0.02	0.021	0.024	0.022	0.025	0.019	0.025	0.02	0.022	0.026	0.034	0.025	0.027	0.026	0.025	0.022	0.021	0.024	0.025	0.02	0.023	0.023	0.022	0.025	0.019	0.0234
3	10.8mm/sec	3.6kg	10%	1.0mm	Every 5 Boards	Leaded	0.026	0.026	0.031	0.023	0.026	0.024	0.028	0.03	0.034	0.025	0.037	0.025	0.046	0.034	0.022	0.027	0.025	0.026	0.023	0.032	0.027	0.024	0.027	0.025	0.031	0.02816
4	13.2mm/sec	4.4kg	15%	1.0mm	Every 10 Boards	Leaded	0.015	0.023	0.024	0.022	0.026	0.03	0.035	0.019	0.031	0.029	0.026	0.027	0.019	0.036	0.028	0.024	0.03	0.02	0.024	0.02	0.03	0.026	0.021	0.028	0.02	0.02532
11	13.2mm/sec	3.6kg	15%	1.0mm	Every 5 Boards	Lead Free	0.023	0.023	0.024	0.022	0.019	0.022	0.022	0.025	0.03	0.023	0.024	0.021	0.027	0.034	0.031	0.025	0.024	0.028	0.025	0.019	0.031	0.023	0.027	0.022	0.024	0.02472
5	10.8mm/sec	4.4kg	10%	0mm	Every 10 Boards	Leaded	0.041	0.035	0.026	0.026	0.034	0.04	0.037	0.027	0.022	0.027	0.031	0.03	0.021	0.033	0.026	0.03	0.025	0.037	0.027	0.025	0.021	0.025	0.027	0.025	0.018	0.02864
12	10.8mm/sec	4.4kg	15%	0mm	Every 5 Boards	Lead Free	0.022	0.023	0.024	0.023	0.024	0.024	0.027	0.02	0.028	0.029	0.025	0.03	0.02	0.027	0.025	0.026	0.031	0.023	0.024	0.026	0.029	0.026	0.024	0.025	0.023	0.02512
6	10.8mm/sec	4.4kg	15%	1.0mm	Every 5 Boards	Leaded	0.027	0.025	0.016	0.027	0.026	0.033	0.028	0.019	0.021	0.021	0.029	0.032	0.018	0.027	0.027	0.027	0.028	0.025	0.028	0.022	0.026	0.029	0.036	0.031	0.022	0.026
13	13.2mm/sec	3.6kg	10%	0mm	Every 10 Boards	Lead Free	0.024	0.023	0.033	0.02	0.03	0.021	0.029	0.029	0.024	0.025	0.028	0.024	0.044	0.03	0.036	0.031	0.023	0.032	0.019	0.022	0.025	0.024	0.027	0.026	0.032	0.02724
7	13.2mm/sec	3.6kg	10%	1.0mm	Every 10 Boards	Leaded	0.028	0.024	0.021	0.024	0.023	0.026	0.027	0.025	0.029	0.027	0.027	0.028	0.024	0.042	0.027	0.028	0.029	0.03	0.026	0.024	0.035	0.032	0.034	0.028	0.025	0.02772
14	10.8mm/sec	3.6kg	10%	0mm	Every 5 Boards	Lead Free	0.021	0.023	0.03	0.025	0.029	0.023	0.024	0.029	0.026	0.03	0.023	0.019	0.032	0.032	0.019	0.027	0.025	0.026	0.021	0.017	0.027	0.023	0.03	0.027	0.02	0.02512
15	13.2mm/sec	4.4kg	15%	0mm	Every 10 Boards	Lead Free	0.02	0.02	0.027	0.027	0.026	0.025	0.021	0.042	0.026	0.039	0.027	0.026	0.03	0.024	0.039	0.031	0.026	0.027	0.024	0.018	0.02	0.022	0.023	0.019	0.023	0.02604
8	13.2mm/sec	4.4kg	10%	0mm	Every 5 Boards	Leaded	0.022	0.023	0.035	0.028	0.022	0.027	0.029	0.03	0.027	0.025	0.027	0.025	0.026	0.026	0.019	0.021	0.027	0.027	0.021	0.021	0.029	0.023	0.029	0.03	0.02	0.02556
16	13.2mm/sec	4.4kg	10%	1.0mm	Every 5 Boards	Lead Free	0.021	0.024	0.03	0.027	0.028	0.027	0.021	0.03	0.024	0.036	0.025	0.025	0.029	0.026	0.038	0.026	0.024	0.023	0.027	0.023	0.023	0.022	0.023	0.012	0.024	0.02552

Solder Paste Volume Variance Data

RunOrder	Print Speed	Squeegee Pressure	Separation Speed	Snap Off	Cleaning Interval	Paste																										Standard Deviation	Variance	Ln Variance
1	10.8mm/sec	3.6kg	15%	0mm	Every 10 Boards	Leaded	0.026	0.024	0.026	0.03	0.03	0.027	0.029	0.029	0.026	0.036	0.022	0.024	0.031	0.027	0.033	0.029	0.029	0.021	0.039	0.038	0.031	0.027	0.029	0.038	0.031	0.004746	2.25E-05	-10.7001
9	10.8mm/sec	4.4kg	10%	1.0mm	Every 10 Boards	Lead Free	0.023	0.019	0.023	0.026	0.026	0.022	0.022	0.028	0.023	0.029	0.028	0.023	0.029	0.033	0.03	0.024	0.022	0.029	0.024	0.022	0.025	0.023	0.024	0.023	0.023	0.0032804	1.08E-05	-11.4335
2	13.2mm/sec	3.6kg	15%	0mm	Every 5 Boards	Leaded	0.034	0.026	0.028	0.028	0.024	0.03	0.025	0.032	0.031	0.026	0.03	0.03	0.035	0.031	0.033	0.032	0.023	0.039	0.025	0.037	0.027	0.027	0.028	0.025	0.035	0.0042513	1.81E-05	-10.9211
10	10.8mm/sec	3.6kg	15%	1.0mm	Every 10 Boards	Lead Free	0.02	0.021	0.024	0.022	0.025	0.019	0.025	0.02	0.022	0.026	0.034	0.025	0.027	0.026	0.025	0.022	0.021	0.024	0.025	0.02	0.023	0.023	0.022	0.025	0.019	0.0032146	1.03E-05	-11.4801
3	10.8mm/sec	3.6kg	10%	1.0mm	Every 5 Boards	Leaded	0.026	0.026	0.031	0.023	0.026	0.024	0.028	0.03	0.034	0.025	0.037	0.025	0.046	0.034	0.022	0.027	0.025	0.026	0.023	0.032	0.027	0.024	0.027	0.025	0.031	0.0053516	2.86E-05	-10.4607
4	13.2mm/sec	4.4kg	15%	1.0mm	Every 10 Boards	Leaded	0.015	0.023	0.024	0.022	0.026	0.03	0.035	0.019	0.031	0.029	0.026	0.027	0.019	0.036	0.028	0.024	0.03	0.02	0.024	0.02	0.03	0.026	0.021	0.028	0.02	0.0052019	2.71E-05	-10.5175
11	13.2mm/sec	3.6kg	15%	1.0mm	Every 5 Boards	Lead Free	0.023	0.023	0.024	0.022	0.019	0.022	0.022	0.025	0.03	0.023	0.024	0.021	0.027	0.034	0.031	0.025	0.024	0.028	0.025	0.019	0.031	0.023	0.027	0.022	0.024	0.0037474	0.000014	-11.1734
5	10.8mm/sec	4.4kg	10%	0mm	Every 10 Boards	Leaded	0.041	0.035	0.026	0.026	0.034	0.04	0.037	0.027	0.022	0.027	0.031	0.03	0.021	0.033	0.026	0.03	0.025	0.037	0.027	0.025	0.021	0.025	0.027	0.025	0.018	0.0060476	3.66E-05	-10.2162
12	10.8mm/sec	4.4kg	15%	0mm	Every 5 Boards	Lead Free	0.022	0.023	0.024	0.023	0.024	0.024	0.027	0.02	0.028	0.029	0.025	0.03	0.02	0.027	0.025	0.026	0.031	0.023	0.024	0.026	0.029	0.026	0.024	0.025	0.023	0.0028331	0.000008	-11.7327
6	10.8mm/sec	4.4kg	15%	1.0mm	Every 5 Boards	Leaded	0.027	0.025	0.016	0.027	0.026	0.033	0.028	0.019	0.021	0.021	0.029	0.032	0.018	0.027	0.027	0.027	0.028	0.025	0.028	0.022	0.026	0.029	0.036	0.031	0.022	0.0047522	2.26E-05	-10.6983
13	13.2mm/sec	3.6kg	10%	0mm	Every 10 Boards	Lead Free	0.024	0.023	0.033	0.02	0.03	0.021	0.029	0.029	0.024	0.025	0.028	0.024	0.044	0.03	0.036	0.031	0.023	0.032	0.019	0.022	0.025	0.024	0.027	0.026	0.032	0.0055848	3.12E-05	-10.3754
7	13.2mm/sec	3.6kg	10%	1.0mm	Every 10 Boards	Leaded	0.028	0.024	0.021	0.024	0.023	0.026	0.027	0.025	0.029	0.027	0.027	0.028	0.024	0.042	0.027	0.028	0.029	0.03	0.026	0.024	0.035	0.032	0.034	0.028	0.025	0.0044208	1.95E-05	-10.8429
14	10.8mm/sec	3.6kg	10%	0mm	Every 5 Boards	Lead Free	0.021	0.023	0.03	0.025	0.029	0.023	0.024	0.029	0.026	0.03	0.023	0.019	0.032	0.032	0.019	0.027	0.025	0.026	0.021	0.017	0.027	0.023	0.03	0.027	0.02	0.0042261	1.79E-05	-10.9329
15	13.2mm/sec	4.4kg	15%	0mm	Every 10 Boards	Lead Free	0.02	0.02	0.027	0.027	0.026	0.025	0.021	0.042	0.026	0.039	0.027	0.026	0.03	0.024	0.039	0.031	0.026	0.027	0.024	0.018	0.02	0.022	0.023	0.019	0.023	0.0062215	3.87E-05	-10.1595
8	13.2mm/sec	4.4kg	10%	0mm	Every 5 Boards	Leaded	0.022	0.023	0.035	0.028	0.022	0.027	0.029	0.03	0.027	0.025	0.027	0.025	0.026	0.026	0.019	0.021	0.027	0.027	0.021	0.021	0.029	0.023	0.029	0.03	0.02	0.0038523	1.48E-05	-11.1182
16	13.2mm/sec	4.4kg	10%	1.0mm	Every 5 Boards	Lead Free	0.021	0.024	0.03	0.027	0.028	0.027	0.021	0.03	0.024	0.036	0.025	0.025	0.029	0.026	0.038	0.026	0.024	0.023	0.027	0.023	0.023	0.022	0.023	0.012	0.024	0.0050093	2.51E-05	-10.5929

Appendix A

Stencil Printing Experiment Effects

```
Estimated Effects for Average (coded units)

Term                           Effect
Constant
Print Sp                     0.002685
Squeegee                    -0.001045
Separati                    -0.001655
Snap Off                    -0.003815
Cleaning                     0.000715
Paste                        0.006055
Print Sp*Squeegee            0.001555
Print Sp*Separati           -0.004695
Print Sp*Snap Off           -0.002375
Print Sp*Cleaning           -0.005985
Print Sp*Paste              -0.003905
Squeegee*Snap Off           -0.001365
Squeegee*Paste              -0.000535
Print Sp*Squeegee*Snap Off  -0.000065
Print Sp*Squeegee*Paste     -0.006755
```

Mean Height Effects

```
Estimated Effects for Ln (coded units)

Term                          Effect
Constant
Print Sp                       0.184
Squeegee                       0.336
Separati                      -0.221
Snap Off                      -0.268
Cleaning                       0.074
Paste                          0.588
Print Sp*Squeegee              0.084
Print Sp*Separati              0.120
Print Sp*Snap Off             -0.026
Print Sp*Cleaning              0.309
Print Sp*Paste                -0.297
Squeegee*Snap Off              0.085
Squeegee*Paste                 0.156
Print Sp*Squeegee*Snap Off     0.019
Print Sp*Squeegee*Paste       -0.169
```

Height Variance Effects,

Appendix A

Stencil Printing Experiment Effects

```
Estimated Effects for Average (coded units)

Term                             Effect
Constant
Print Sp                       0.000140
Squeegee                      -0.001020
Separati                      -0.000420
Snap Off                      -0.001360
Cleaning                       0.000340
Paste                          0.002280
Print Sp*Squeegee             -0.000700
Print Sp*Separati              0.000340
Print Sp*Snap Off              0.000060
Print Sp*Cleaning             -0.000120
Print Sp*Paste                -0.001100
Squeegee*Snap Off              0.000460
Squeegee*Paste                -0.001300
Print Sp*Squeegee*Snap Off     0.000460
Print Sp*Squeegee*Paste       -0.000220
```

Mean Volume Effects.

```
Estimated Effects for Ln (coded units)

Term                             Effect
Constant
Print Sp                           0.24
Squeegee                           0.05
Separati                          -0.18
Snap Off                          -0.13
Cleaning                           0.24
Paste                              0.30
Print Sp*Squeegee                  0.18
Print Sp*Separati                  0.22
Print Sp*Snap Off                 -0.01
Print Sp*Cleaning                  0.24
Print Sp*Paste                    -0.58
Squeegee*Snap Off                  0.13
Squeegee*Paste                     0.04
Print Sp*Squeegee*Snap Off         0.10
Print Sp*Squeegee*Paste           -0.21
```

Volume Variance Analysis: Effects

Appendix B

Cross Section Scores

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
1F	1	0	3	2	3	1	1
	2	0	2	1	4	2	1
	3	0	1	1	0	0	1
	4	0	2	1	0	0	1
	5	0	3	1	5	2	1
	6	0	1	1	3	1	1
	7	0	2	1	2	1	1
	8	0	3	2	3	1	2
	9	0	2	1	0	0	1
	10	0	4	2	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
2F	1	0	5	2	0	0	1
	2	0	2	1	2	1	1
	3	0	1	1	0	0	1
	4	0	2	1	2	1	1
	5	0	1	1	0	0	1
	6	0	2	1	2	1	1
	7	0	3	1	3	1	1
	8	0	3	2	3	1	1
	9	0	2	1	2	1	1
	10	0	3	1	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
3F	1	0	1	1	0	0	1
	2	0	2	1	0	0	1
	3	0	2	1	2	1	1
	4	0	3	1	2	3	1
	5	0	3	1	2	1	1
	6	0	1	1	2	1	1
	7	0	2	1	0	0	2
	8	0	1	1	0	0	1
	9	0	2	1	0	0	1
	10	0	2	1	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
4F	1	0	3	1	3	1	1
	2	0	1	2	0	0	1
	3	0	4	2	0	0	1
	4	0	4	2	0	0	1
	5	0	5	2	2	2	1
	6	0	5	2	0	0	2
	7	0	3	2	0	0	1
	8	0	3	1	3	1	1
	9	0	2	2	2	1	1
	10	0	2	1	0	0	2

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
5F	1	0	3	1	4	1	1
	2	0	1	2	2	2	1
	3	0	2	2	0	0	1
	4	0	1	1	0	0	1
	5	0	2	1	0	0	1
	6	0	1	1	0	0	1
	7	0	1	2	2	2	1
	8	0	1	1	0	0	1
	9	0	2	1	2	1	1
	10	0	2	2	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
6F	1	0	4	2	0	0	2
	2	0	2	2	0	0	2
	3	0	2	1	0	0	1
	4	0	3	1	0	0	1
	5	0	4	1	2	1	1
	6	0	1	1	2	1	1
	7	0	3	2	0	0	1
	8	0	1	1	3	1	1
	9	0	3	2	5	2	1
	10	0	3	2	3	2	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
7F	1	0	2	1	2	1	1
	2	0	1	1	0	0	1
	3	0	2	2	0	0	1
	4	0	2	1	2	1	1
	5	0	1	1	0	0	1
	6	0	1	1	0	0	1
	7	0	2	1	0	0	1
	8	0	2	1	0	0	1
	9	0	1	1	0	0	1
	10	0	2	1	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
8F	1	0	2	1	0	0	1
	2	0	1	1	0	0	1
	3	0	1	1	0	0	1
	4	0	2	1	0	0	1
	5	0	2	1	0	0	1
	6	0	1	1	0	0	1
	7	0	1	1	0	0	1
	8	0	1	1	0	0	1
	9	0	1	1	0	0	1
	10	0	1	1	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
9F	1	0	4	2	7	3	2
	2	0	3	2	0	0	2
	3	0	4	1	6	2	1
	4	0	3	1	5	1	1
	5	0	2	2	1	0	1
	6	0	2	1	4	2	1
	7	0	4	1	6	1	1
	8	0	4	2	6	2	2
	9	0	2	1	0	0	1
	10	0	2	1	3	1	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
10F	1	0	2	1	2	1	1
	2	0	1	1	0	0	1
	3	0	3	1	2	1	1
	4	0	1	1	0	0	1
	5	0	2	1	0	0	1
	6	0	1	1	0	0	1
	7	0	2	1	0	0	1
	8	0	3	2	0	0	1
	9	0	2	1	0	0	1
	10	0	3	2	0	0	2

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
11F	1	0	2	2	0	0	1
	2	0	2	1	0	0	1
	3	0	1	1	2	1	1
	4	0	3	1	3	2	1
	5	0	2	1	2	1	1
	6	0	1	1	0	0	1
	7	0	2	1	0	0	1
	8	0	1	1	0	0	1
	9	0	2	1	2	1	1
	10	0	3	1	3	3	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
12F	1	0	2	1	0	0	1
	2	0	1	1	0	0	1
	3	0	2	1	2	2	1
	4	0	1	1	0	0	1
	5	0	2	1	0	0	1
	6	0	2	1	0	0	2
	7	0	1	1	2	1	1
	8	0	2	1	2	1	1
	9	0	1	1	0	0	1
	10	0	1	1	2	1	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
13F	1	0	2	2	2	1	1
	2	0	1	1	0	0	1
	3	0	2	1	2	3	1
	4	0	2	1	0	0	1
	5	0	3	2	2	1	1
	6	0	4	2	4	1	1
	7	0	3	1	3	1	2
	8	0	1	1	0	0	1
	9	0	2	1	0	0	2
	10	0	3	1	2	1	2

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
14F	1	0	2	1	2	1	1
	2	0	2	1	0	0	1
	3	0	2	2	0	0	1
	4	0	3	2	2	1	1
	5	0	2	2	0	0	2
	6	0	2	2	0	0	1
	7	0	3	2	2	1	1
	8	0	3	3	0	0	1
	9	0	2	2	0	0	1
	10	0	2	2	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
15F	1	0	2	1	3	1	1
	2	0	1	1	0	0	1
	3	0	3	2	4	1	1
	4	0	2	1	3	1	1
	5	0	1	1	0	0	1
	6	0	1	1	2	1	1
	7	0	2	1	0	0	1
	8	0	3	1	3	1	1
	9	0	2	2	0	0	1
	10	0	2	2	0	0	1

Part No.	Ball No.	Defects	Joint Formation	Wetting	Size of Void	Freq. of Void	Alignment
16F	1	0	2	1	2	1	1
	2	0	2	1	2	1	1
	3	0	3	1	4	2	1
	4	0	4	1	5	2	1
	5	0	2	1	2	1	1
	6	0	1	1	2	1	1
	7	0	2	1	3	1	1
	8	0	1	1	0	0	1
	9	0	1	1	0	0	1
	10	0	2	1	2	1	1

Appendix B Average Weighted Scores for Reflow Experiment

Tin Lead Data

StdOrder	RunOrder	Belt Speed	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Ball 1	Ball 2	Ball 3	Ball 4	Ball 5	Ball 6	Ball 7	Ball 8	Ball 9	Ball 10	Average Weighted Score
15	1	12	170	185	200	220	280	0.18	0.39	0.36	0.33	0.47	0.36	0.64	0.67	0.47	0.18	4.047
4	2	14	170	175	190	220	280	0.46	0.39	0.36	0.18	0.33	0.29	0.18	0.18	0.18	0.18	2.73
1	3	12	160	175	190	220	270	0.18	0.18	0.18	0.46	0.18	0.18	0.26	0.33	0.36	0.36	2.67
11	4	12	170	175	200	230	270	0.33	0.33	0.61	0.61	0.26	0.26	0.26	0.18	0.18	0.18	3.2
9	5	12	160	175	200	220	280	0.18	0.56	0.56	0.33	0.18	0.18	0.33	0.18	0.18	0.18	2.86
7	6	12	170	185	190	220	270	0.18	0.18	0.18	0.18	0.18	0.26	0.46	0.61	0.61	0.46	3.3
8	7	14	170	185	190	230	270	0.33	0.41	0.33	0.46	0.33	0.18	0.18	0.18	0.18	0.18	2.76
16	8	14	170	185	200	230	280	0.54	0.56	0.18	0.36	0.49	0.46	0.36	0.74	0.36	0.18	4.23
13	9	12	160	185	200	230	270	0.49	0.4	0.55	0.6	0.32	0.6	0.29	0.57	0.29	0.29	4.4
5	10	12	160	185	190	230	280	0.26	0.54	0.33	0.26	0.44	0.29	0.33	0.48	0.33	0.33	3.59
12	11	14	170	175	200	220	270	0.38	0.18	0.33	0.51	0.48	0.59	0.44	0.43	0.33	0.33	4
10	12	14	160	175	200	230	280	0.18	0.18	0.18	0.18	0.29	0.29	0.18	0.46	0.46	0.29	2.69
14	13	14	160	185	200	220	270	0.18	0.46	0.18	0.18	0.18	0.33	0.29	0.18	0.18	0.56	2.72
3	14	12	170	175	190	230	280	0.46	0.46	0.18	1.1	0.74	0.92	0.18	0.46	0.46	0.46	5.42
2	15	14	160	175	190	230	270	0.18	0.18	0.18	0.18	0.46	0.18	0.49	0.62	0.64	0.64	3.75
6	16	14	160	185	190	220	280	0.46	0.18	0.46	0.46	0.18	0.57	0.29	0.29	0.29	0.33	3.51

Lead-Free Data

StdOrder	RunOrder	Belt Speed	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Ball 1	Ball 2	Ball 3	Ball 4	Ball 5	Ball 6	Ball 7	Ball 8	Ball 9	Ball 10	Average Weighted Score
9	1	12	170	210	240	245	315	0.71	0.46	0.18	0.26	0.59	0.48	0.46	0.74	0.26	0.49	4.63
10	2	14	170	210	240	265	315	0.57	0.46	0.18	0.46	0.18	0.46	0.64	0.71	0.46	0.34	4.46
12	3	14	180	210	240	245	280	0.18	0.26	0.46	0.41	0.54	0.38	0.32	0.18	0.26	0.26	3.247
5	4	12	170	220	230	265	315	0.64	0.25	0.49	0.49	0.67	0.6	0.41	0.64	0.53	0.29	5.01
8	5	14	180	220	230	265	280	0.74	0.35	0.33	0.18	0.26	0.18	0.35	0.18	0.46	0.33	3.36
7	6	12	180	220	230	245	280	0.52	0.36	0.26	0.34	0.62	0.38	0.41	0.48	0.66	0.56	4.59
2	7	14	170	210	230	265	280	0.46	0.18	0.33	0.46	0.18	0.18	0.26	0.26	0.18	0.26	2.75
6	8	14	170	220	230	245	315	0.26	0.18	0.18	0.26	0.26	0.18	0.18	0.18	0.18	0.18	2.04
3	9	12	180	210	230	265	315	0.75	0.44	0.72	0.84	0.33	0.46	1.02	0.82	0.26	0.56	6.203
4	10	14	180	210	230	245	315	0.46	0.18	0.54	0.18	0.26	0.18	0.26	0.41	0.26	0.44	3.17
13	11	12	170	220	240	265	280	0.33	0.26	0.38	0.49	0.46	0.18	0.26	0.18	0.46	0.44	3.44
14	12	14	170	220	240	245	280	0.26	0.18	0.36	0.18	0.26	0.29	0.38	0.46	0.18	0.38	2.93
15	13	12	180	220	240	245	315	0.53	0.18	0.33	0.26	0.61	0.89	0.67	0.18	0.29	0.57	4.507
1	14	12	170	210	230	245	280	0.46	0.26	0.33	0.61	0.36	0.33	0.61	0.48	0.33	0.33	4.1
11	15	12	180	210	240	265	280	0.56	0.18	0.81	0.56	0.18	0.38	0.26	0.64	0.33	0.33	4.23
16	16	14	180	220	240	265	315	0.46	0.46	0.54	0.67	0.46	0.38	0.56	0.18	0.18	0.46	4.35

Appendix C – Published Papers

O'Neill, S. and Donovan, J., (2004), "Replicate or Duplicate Measurements – The Consequence of Misdiagnosis: A Case Study", *10th ISSAT International Conference on Quality and Reliability in Design*, Las Vegas, NV, pp. 335 – 340.

O'Neill, S., J. O'Donovan, C. Ryan, J. Punch, E. Murphy, (2004) "Experimental design on a lead-free SMT process measuring qualitative and quantitative responses", In: Proceedings of 4th Annual ENBIS Conference - European Network for Business and Industrial Statistics, Copenhagen, September 22-23, 2004.

O'Neill, S., Donovan, J. and Ryan, C., "A Qualitative Method for Determining the Quality of BGA Solder Joints in a Lead-Free Process" In Proceedings of Institute of Technology Blancardstown Research Conference, Blanchardstown, Dublin, ITB Journal No.9 pp. 188 – 196.

Ryan C., S. O'Neill, J. Punch, B. Rodgers, E. Murphy, J. Donovan, (2004) "Optimising Lead-Free Screen-Printing and Reflow Parameters" In: Proceedings of The Tenth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, Las Vegas, June 1-4, 2004. IEEE publications, 664-668.

Ryan C., J. Punch, B. Rodgers, S. O'Neill, E. Murphy, J. Donovan, G. Heaslip, (2004) "An Investigation of the Lead-Free Surface Mount Soldering Process: Solder Joint Evaluation and Process Optimisation" Accepted for publication in: Proceedings of International Mechanical Engineering Congress and Exposition, Annual Meeting of ASME, Anaheim, Nov 13-19, 2004.