DESIGN AND STEPS TO IMPLEMENTATION OF LEAD-FREE MANUFACTURING

by

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ABSTRACT

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Design and Steps to Implementation of Lead-free Manufacturing

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Lead is no longer used in paints or gasoline due to the harmful effects caused from internal consumption and inhalation of lead. Unfortunately, the steps taken to reduce or control the harmful usage of lead in these cases were a reactive rather than a proactive solution. The electronics manufacturing industry now faces a similar situation. Over 80% of the lead used today can be found in automobile batteries. This means the electronics manufacturing industry does not account for a very large percentage of the total lead usage, but it is the way these devices are someday discarded that is of concern. Lead automobile batteries present a minimal amount of risk to the general public because the lead is contained and it has a well-established recycle system. Electronic devices containing lead are finding their way into landfills and a concern is that the lead may eventually migrate into the drinking water systems. Although there are no cases of such yet, many manufacturers and legislatures would prefer to eliminate the possibility of harm to the general public and the environment. With personal computers and various types of electronic devices becoming more available to the general public, the amount of electronic waste that is dumped into landfills will increase. This will also increase the possibility of lead migration into the water systems. The elimination of lead in electronic devices has now become the trend and an industry wide conversion appears imminent. The question is no longer if lead-free, but rather, when lead-free. Therefore, manufacturers must now consider the key characteristics of successful lead-free implementation if they are to remain competitive.

The purpose of this paper was to explore the key characteristics to consider when implementing to a lead-free electronics manufacturing system. XYZ Company was the participating company in this study and was evaluated by using the characteristics determined above. At the time of this research, XYZ had expressed great interest in exploring lead-free manufacturing and an eventual implementation.

The results of the study showed various key characteristics to consider when implementing a lead-free manufacturing system. It examined the selection of lead solders and components, evaluated current and new manufacturing equipment, and detailed the differences in inspection and training.

In conclusion, suggestions for successful steps to lead-free implementation were offered to assist XYZ Company in planning for future implementation. Furthermore, suggestions were offered for further similar studies.

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Cal F. Her

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CHAPTER I

INTRODUCTION

1.1 Research Background

Within the electronic manufacturing industry, lead-free manufacturing has been and continues to be a topic of great discussion. There are three reasons why lead-free manufacturing has become such an important topic. They are environmental and safety issues, fear of regulation, and competition.

The environmental and safety issues surrounding lead is nothing new. Lead has long been a substance that has attracted the attention of environmentalists. At least in the US, lead-based paint and leaded gasoline for example, no longer have traces of lead in them due to the harmful effects caused by lead consumption and inhalation. Further details regarding the harmful effects of lead and a history of lead will be provided in Chapter 2.

In order to ensure that lead is no longer used in paints or gasoline, regulations were put into place and enforced. This is the second reason why lead-free has become such an important topic. The fear of regulatory intervention is another reason why much attention has been shifted to lead-free substitutes. The restrictions placed on paints and gasoline is a clear indicator to electronics manufacturers that legislators will indeed take appropriate measures to prohibit the use of lead if necessary.

Aside from the pressures brought on by environmentalists and legislators, there is still another factor to consider. Competition from manufacturers who’ve transitioned to lead-free either because of established regulations or through voluntary implementation is of concern. The ability to produce satisfactory finished goods without endangering the environment with hazardous materials provides manufacturers with a solid selling advantage. It is hard to imagine a company wanting to be labeled as a manufacturer of environmentally unsafe, toxic consumer products, especially when adequate substitutes are available.

The electronics industry on the international side appears to have accepted lead-free substitutes. The primary reason for this change is due to legislation enacted to promote a healthier environment. If there are only lead-free materials allowed in the market, manufacturers really have no other alternative. How does the international conversion affect the US? The electronics manufacturing industry is a global industry. International and US partnerships will be in jeopardy if US manufacturers cannot provide adequate services to their international partners. Whether or not there is legislation in the future to challenge US manufacturers, global competitiveness will. Environment friendly manufacturing is basically a common sense approach to manufacturing. If there are effective environment friendly substitutes available for current applications, then they will be used instead.

Electronics manufacturers in the US have begun evaluating alternatives to lead. There are a few reasons why the US market is lagging behind the international lead-free transition. The cost of lead-free materials is significantly higher than the common lead-based materials. Lead is a readily available substance, inexpensive and a long standard of the electronics industry. Lead is a substance that works well with all current soldering applications because it has characteristics that are suitable for the electronics industry.

By transitioning to lead-free substitutes, further testing and adequate research is needed to ensure fit and function, adding to the overall cost. Additional training needed to operate and understand new technology and the purchase of new equipment are additional cost concerns. The melting points of lead-free solders are typically higher than lead-based solders, posing questions regarding the stability of electrical components. If new component design and development is needed to maintain stability at higher temperatures, then this again will contribute to the overall cost. Components that cannot tolerate such temperatures may require additional installation procedures. Lead-free is not simply a substitution of one thing for another. It requires significant changes to nearly every part of the entire manufacturing system involving materials, machines, and the methods used.

Another reason why US manufacturers are behind the rest of the world is due to the lack of demand for lead-free products. Consumers have not required lead-free substitutes at an alarming rate. Furthermore, there is no current legislation in the US prohibiting the use of lead-based materials in electronics manufacturing. Without new legislation to prohibit the use of lead, some manufacturers may resist this new trend as long as they can remain competitive. They can live with the mentality that if your customers don’t ask for it, then don’t do it.

The electronics manufacturing services (EMS) department of the XYZ Company is a contract manufacturing (CM) company. Contract manufacturing has gained significant popularity over the past few years largely due to the increasing cost to manufacture. XYZ Company’s focus is primarily in the high mix, low volume end of the electronics industry. High mix refers to the different types of components that can be placed on a printed circuit board (PCB). There are two main types of components that can be placed onto a PCB, surface mount and throughhole components. Surface mount components are placed onto solder screened pads of a PCB with very high-speed placement machines. These machines have magazines loaded with surface mount components allowing the boards to be built in a short period of time. However, if the board should also have throughhole components, there must be a separate process to place the throughhole components. The placement of throughhole components can be done by hand or machine, depending on the volume. If there are both types of components on the top and bottom sides of the PCB, then more setup is needed for each process. A high-speed manufacturing line normally operates with a low mix of components allowing for a larger throughput by decreasing the number of processes. Original equipment manufacturing (OEM) companies usually fall into this category because they focus primarily on one family of similar products.

XYZ Company's production runs are done in batches to allow for repetitive changeover. A typical production flow for XYZ Company could involve all of the following:

1. Screen solder paste onto PCB with stencil printer.
2. Place surface mount components with pick and place machine.
3. Hand place components that cannot be placed by machine.
4. Solder components onto PCB with reflow oven.
5. Wash the boards.
6. If the board is double sided, repeat steps 1-5.
7. Inspect solder connections with optical inspection machine.

8. Hand place throughhole components.
9. Solder throughhole components with wave machine.
10. Hand solder special components.
11. Visual inspection.
12. Rework.

As a contract manufacturer, XYZ Company's customers range from medical to electronic devices and computers as well as military projects. Product specifications and materials for each are different and unique. The use of eutectic tin-lead is, however, a common similarity. A lead-free transition will require contract manufacturers to become familiar with more varieties of lead-free solders, components, and PCBs.

Because of the recent interests in lead-free substitutes, customers for XYZ Company have inquired about the company's intentions with lead-free manufacturing. This prompted the company to take a closer look at lead-free manufacturing especially the critical things to consider with a lead-free implementation.

1.2 Research Problem

Because of environmental pressures, fear of regulation, and competition, the purpose of this study is to research lead-free to identify the attributes, analyze the benefits, and identify a specific lead-free implementation model.

1.3 Need Statement

As stated above, several of XYZ Company's customers have inquired about the company's lead-free objectives. With the approval of XYZ Company's management team, this research study is being conducted to obtain further knowledge of lead-free alternative materials as well as their effects on the machines and methods involved. As the industry begins to evaluate lead-free as a standard in their practices, manufacturers must take measures to ensure they can remain competitive. In order to remain competitive when the entire industry does convert to lead-free, manufacturers must ensure a successful lead-free implementation. A solid implementation will ensure an immediate and positive response to lead-free demands or new regulation. An unsuccessful implementation could prove costly in terms of time, money, and competitiveness. Therefore, a better understanding of the critical elements of a lead-free manufacturing system is needed.

1.4 Assumptions

- The researcher assumes criteria for reviewing lead-free implementation is researchable.
- The researcher assumes analysis of the criteria is researchable.
- The researcher assumes that a generalized implementation is possible.

1.5 Limitations

- The researcher was limited to the resources available.
- The researcher was limited to the time available to complete the study.
- A lead-free manufacturing company was not used.
- A cost analysis of lead-free substitutes was not done.

CHAPTER II

LITERATURE REVIEW

2.1 Overview

Chapter 1 introduced three reasons why lead-free alternative materials are being evaluated by manufacturers and more widely adopted by segments of the industry. The main reasons for this are environmental and safety issues, fear of regulation, and competition. These topics will be further detailed in this chapter along with some history of lead and its evolution into modern electronics manufacturing.

2.2 History of lead

Lead was first discovered in Turkey around 6500 BC, but the first significant production of lead did not occur until about 3000 BC. The Romans and Greeks used lead around 500 BC to 300 AD. Even then, the Greeks documented clinical descriptions of lead poisoning. Medical authorities in the US first diagnosed childhood lead poisoning in the late 1800s. By the early 1900s, it was confirmed that lead poisoning in children was directly linked to lead-based paints. Soon after, France, Belgium and Austria placed a ban on white-lead interior paints. (Markowitz, 2000)

The Industrial Revolution greatly extended the use of soldering technology by the availability of portable heat sources such as oxygen-gas torches and the electric soldering iron. These allowed the use of soft soldering in plumbing, the sealing of food and water containers, and later, the fabrication of larger structures like automobile radiators. The use of solder as an alloy of tin and lead began with the tin can, at about the turn of the century. Alloying lead and tin made heat joining of the metals of tin cans both economical and practical. Tin cans were used primarily for food storage. (Dezettel, 1968)

It was in the early 20th century that soldering entered the electronics industry as a reliable means of connecting copper wires for power and signal transmission. In those early applications, the solder joint served primarily to ensure electrical continuity rather than strength as parts were mechanically fastened to the panel. With the introduction of the silicon-chip technology, the electronics industry observed a continuous trend of miniaturization. The reduction of package-size requirements and the demand for the solder joint to provide both mechanical as well as an electrical connection challenged the properties of tin-lead solder. In order to maintain stronger electrical connections, printed circuit boards were made with lead-based finishes and components with lead-based connectors. Eventually, tin-lead solder emerged as the primary soldering alloy used throughout the entire electronics industry.

Lead is a material that is easily extracted and refined with relatively low energy costs and it has a range of useful properties including low melting temperatures and good conductivity. The problem with lead is its toxicity. This is why lead is being eliminated in all areas where an effective substitute can be used as with unleaded gasoline and lead-free paints.

2.3 Environmental and Safety Issues

Lead was added to gasoline in the 1920s to reduce engine knock and enable engineers to design cars with higher compression in the cylinders, permitting greater power and efficiency. Other octane boosters that early car designers experimented with included ethyl alcohol, also known as ethanol or grain alcohol. The fact that ethanol is plentiful and easy to make is why it was rejected by the leaders at General Motors and duPont. They wanted an additive they could control and profit from like tetraethyl lead (TEL), which could also be patented. (Kitman, 2000)

At that time, prominent health and safety experts including officials at the US Public Health Service expressed concern about adding TEL to gasoline. In 1922, the Surgeon General himself submitted a letter to GM interim president Pierre duPont expressing concern about the usage of TEL in gasoline. (Kitman, 2000) By 1926, a special health and safety committee had been formed to investigate the dangers of TEL, but they could not find any solid grounds for banning its use. However, the committee cautioned that if leaded gasoline became widespread, further studies would be warranted. Over the next 40 years, all research of TEL's health effects were underwritten by GM, Standard Oil, duPont and trade associations for the lead industry. The many documented warnings from health officials went unnoticed.

With advancements in medical science and technology, leaded gasoline was finally banned around the 1970s. The many cases surrounding lead poisioning contributed greatly to the banning of lead in gasoline. Since the ban, American lead blood levels have decreased almost 80 percent. In a 1988 report to Congress, lead expert Dr. Paul Mushak estimated that 68 million children had toxic exposures to lead from gasoline during 1927 to 1987. (Kitman, 2000) Furthermore, a 1985 EPA study estimated that as many as 5000 Americans were dying annually from lead-related heart disease prior to the lead phase-out. This example of lead removal from gasoline shows how dangerous the toxicity of lead is to its immediate users. This is similar to leaded paints, but the toxicity of lead in the electronics industry is somewhat different.

The toxicity of lead to its immediate users in the electronics industry is not the main reason for its removal. It is the redistribution of the material, like obsolete personal computers, back into the environment via landfills that presents a long-term problem for groundwater purity. The following table shows the different risks associated to lead. (Warwick, 1999)

Table 2.1 LEAD INGESTION ROUTES

Route of Exposure	Toxic Risk	Comments
Absorption	Low	Inorganic Pb not absorbable through skin, only certain organic Pb compounds absorbable
Ingestion	Moderate	10% of ingested Pb absorbed in gastro-intestinal tract
Inhalation	High	30%±10% Pb fumes and dusts retained by lungs

Circuit boards contain about 7-8% solder with a 2-3% lead concentration. Components placed onto the circuit boards usually have less than 1% by weight of lead content. It would appear that the use of lead in the electronics industry is relatively minute. Besides, it is highly unlikely that solders on circuit boards can be swallowed, absorbed, or inhaled. The concern, rather, is that increased amounts of lead-based components dumped into landfills will someday contaminate the water systems allowing for a moderate toxic risk. USA today published statistics and projections on June 22, 1999 concerning the growing number of personal computers in America.

- Over 44% of US households own a PC in 1999.
- A PCs life will reduce from 3 years to 2 years by 2007 primarily due to continuous technological advancements and decreasing PC and PC component prices.
- The number of PCs becoming obsolete each year will grow from the current 20MM to over 60MM by 2003.
- Many obsolete PCs are in storage because there is no easy way to dispose of them.
- Only 11% of processors are recycled. (Rae, 2000)

Aside from personal computers, printed circuit boards can be found in every kind of electrical device or machine ranging from children's toys to expensive supercomputers. Advancements in technology will only continue to push the demand for circuit boards. Even without the presence of other mechanisms, the growing number of PCs alone clearly indicate the quantity of circuit boards going into landfills will continue to increase. This will also increase the level of lead in landfills. With the growing concern that lead will migrate into the drinking water system, there has been a strong move toward a lead-free manufacturing environment.

2.4 Lead-free

Over the last ten years, there have been a large number of publications describing work into lead-free electronics soldering. They have come from all regions of the world and from academic organizations, individual companies and consortia. These publications have come about due to the rising concerns by environmentalist, legislators, and manufacturers over the continued use of a known toxin, lead. Although a number of these studies have culminated in production trials, these have invariably been on a limited scale and they were essentially a demonstration, rather than the first step to implementation. This situation has changed significantly since the fourth quarter of 1998. In quick succession, the second draft of a proposed European Directive was published and major players in the Japanese electronics industry voiced their intent to eliminate lead in the next few years. (Warwick, 1999) More to the point, products actually went on sale that had been assembled by a lead-free process. There is now a clear indication that many manufacturers will be running lead-free assembly processes in at least part of their production. The roll out of lead-free soldering will then depend on technical roadblocks and commercial pressures. It is quite possible that there will be rapid adoption in some sectors, while others remain rooted to lead solders. One factor that may change the picture is the advance of contract manufacturing. This may be a powerful driver for harmonization, not just in moving to lead-free soldering, but in the selection of a limited number of general-purpose alloys.

2.5 Fear of Regulation

The use of lead in the electronics industry began receiving attention from environmentalist and legislators a little over 10 years ago. In fact, environmentalists have been involved with the methods and materials used in the electronics industry before the new movement toward lead-free manufacturing. The enactment of the Clean Air Act of 1990 and the Montreal Protocol eliminated the use of chlorinated fluorocarbon solvents. (Whiteman, 2000) These solvents were used primarily as cleaners for electronics hardware and discovered to be a threat to the environment. In response to the legislation, new cleaning and soldering technologies were developed and implemented. This example of legislative involvement in a different area of the electronics industry provides manufacturers with the notion that future involvement in other areas like lead is inevitable. The fear of new legislation is a major reason for the lead-free movement.

2.6 Competition

Consumers world-wide surveyed by Motorola in 1999 indicated that 44% had recently purchased a product specifically because it was better for the environment and 76% would switch brands to an environmentally safer product if the price and quality were equal.

In consumer electronics, the Japanese companies are clearly the leaders in this field. They have all made public commitments to move to lead-free. The lead-free products are labeled with a green leaf or other similar symbol and should sell at equivalent prices.

The lead-free message is clear. Where available, consumers want environmentally safer products that are comparable to the brands they like. As the leading electronics companies become more committed to lead-free, especially at equivalent prices, it appears that consumers will have that option available to them. Manufacturers must now contend with lead-free as a competitive selling edge.

2.7 Recent developments

The second draft of the proposed European Commission Directive on Waste from Electronic and Electrical Equipment (WEEE) has three basic aims. The first is to prevent waste of electronic and electrical equipment. The second purpose is to promote re-use, recycling and recovery of such waste. Finally, minimize risks and impact to the environment associated with treatment and disposal of end-of-life electronic and electrical equipment. As part of these objectives, it is expected that the use of hazardous materials will be phased out. All EU member states will be obliged to ensure that the use of lead, mercury, cadmium, hexavalent chromium and halogenated flame retardant is phased out by January 2004. However, there are rumors that this date might be extended until 2006. (Nimmo, 2000) Regardless, lead-free is on its way.

The Danish Environment Agency is proposing a statutory order on prohibition of import, marketing and manufacture of lead and products containing lead. This order will affect the import, marketing and manufacture of lead and certain products containing lead. The Japanese Ministry of Trade (MITI) has drafted a similar recycling law to that of the EC that will require consumer and business users of electrical appliances to return end-of-life goods to retailers or local authorities for recycling.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

This chapter is about the two major research methodologies available to researchers today, quantitative and qualitative research. A brief description of the two methodologies will be provided with additional detail given to qualitative research, as this study will be qualitative. The chapter will also outline the design of the research.

3.2 Method of Study

Research methods usually fall into two major categories, quantitative and qualitative. Quantitative data are often represented numerically in the form of means, percentages, or frequency counts. This kind of data can be measured. Quantitative research is typically designed to test relatively specific predictions and seeks to study the variables that are already known.

The goal of qualitative research is to obtain a general, overall appreciation of a phenomenon, highlighting interesting aspects and perhaps generating specific hypotheses. Thus, qualitative research provides an initial description of a phenomenon, whereas quantitative research aims to investigate its various details. In other words, qualitative research is looking for the critical variables that need to be further studied.

Strauss and Corbin (1990) claim that qualitative methods can be used to better understand any phenomenon about which little is yet known. They can be used to gain new perspectives on things about which much is already known, or to gain more indepth information that may be difficult to convey quantitatively. Thus, qualitative methods are appropriate in situations where one needs to first identify the variables that might later be tested quantitatively, or where the researcher has determined that quantitative measures cannot adequately describe or interpret a situation. Research problems tend to be framed as open-ended questions that will support discovery or new information. In an article in the Journal of Technology Education, Marie Hoepfl provides a list of features associated with qualitative research methods (Hoepfl, 1997).

1. Qualitative research uses the natural setting as the source of data. The researcher attempts to observe, describe and interpret settings as they are, maintaining what Patton calls an "empathic neutrality" (Patton, 1990, p. 55)
2. The researcher acts as the "human instrument" of data collection.
3. Qualitative researchers predominantly use inductive data analysis.
4. Qualitative research reports are descriptive, incorporating expressive language and the "presence of voice in the text" (Eisner, 1991, p. 36).
5. Qualitative research has an interpretive character, aimed at discovering the meaning events have for the individuals who experience them, and the interpretations of those meanings by the researcher.
6. Qualitative researchers pay attention to the idiosyncratic as well as the pervasive, seeking the uniqueness of each case.
7. Qualitative research has an emergent (as opposed to predetermined) design, and researchers focus on this emerging process as well as the outcomes or product of the research.

8. Qualitative research is judged using special criteria for trustworthiness.

The nature of this study is exploratory as it seeks to create a new body of knowledge. The critical characteristics of a lead-free, manufacturing system needs to be researched before those characteristics can be studied quantitatively. Quantitative research cannot be done in this case because there is no data available for numerical analysis. Therefore, this study will involve the use of qualitative methods.

3.3 Research Design

The research design will involve a thorough research and review of available literature. The information gathered from the research will provide the researcher with adequate resources for developing a model for lead-free implementation, highlighting key characteristics of the system. The model will allow the researcher to evaluate the participating company's system and formulate recommendations for successful steps to implementation. Furthermore, the model will allow generalizations to be made for other manufacturers to consider when making a lead-free implementation.

The design will take a look at the materials, machines and methods used in lead-free manufacturing. A careful review of each will provide better understanding of the critical characteristics of a lead-free system. A breakdown of the design topics is listed below.

1. Materials
    a. Solder – characteristics of more common lead-free alloys compared to eutectic tin-lead.
    b. Printed circuit boards – characteristics of lead-free finishes.

   c. Components – structural characteristics due to demanding increases in solder melting temperatures.

2. Machines
   a. Stencil printer – characteristics of lead-free solders during pasting cycles.
   b. Pick & place machine – characteristics of machines with usage lead-free solders.
   c. Reflow oven – machine characteristics due to demanding increases in solder melting temperatures.
   d. Cleaning – machine characteristics with lead-free usage.
3. Methods
   a. Visual inspection – methods needed for adequate visual inspection.
   b. Optical inspection – characteristics of advanced optical inspection machines with lead-free usage.
   c. New processes – new processes and methods needed throughout the different stages of manufacturing to ensure proper lead-free handling. This will include tracking methods for the different types of alloys being used.

The areas of the design with greater significance will be explained in more detail. After the above topics have been researched and detailed, recommendations will be made.

CHAPTER IV

STUDY

4.1 Introduction

This chapter will investigate the materials, machines, and methods to consider when implementing a lead-free system. Each will contribute to the overall performance of the lead-free system. Some will involve significant changes while others will remain relatively unchanged. The materials category is the area with the most distinct differences. Because all of the materials have some level of lead in them with solder having the most, the characteristics of the lead-free alternative materials are noticeably different ranging from higher solder melting temperatures to duller looking solder joints. With duller looking solder joints, visual and optical inspection techniques will require new training in order to differentiate between the different looking solder joints.

The use of lead-free alternative materials will not affect most of the machines involved. Pick and place machines basically move components from magazines onto PCB pads, therefore, not impacted by lead-free changes. On the other hand, reflow ovens will require more careful profiling. Most ovens are capable of handling the increased temperatures needed for lead-free solders, but the many different types of solder alloys will produce a wider array of oven profiles.

4.2 Lead-free materials

When referring to lead-free, what is it that needs to be lead-free in the electronics manufacturing industry? It is the materials used. The most common solder used to bond components with printed circuit boards has lead in it. Printed circuit boards have lead in the pads to allow better connectivity with the solder. The leads on electronic components have traces of lead in it also to help bond with the solder and the surface of the PCB pads. An industry wide change to lead-free will involve adequate substitutions for each of these materials.

4.2.1 Solder

Since the beginning of lead-free, solder has been examined and researched more than any other material. The main reason for this is the fact that there is more lead in solder than there is in PCBs and electronic components. Since manufacturers have begun and continue to investigate lead-free solders, there have been many possible substitutes introduced.

The top two criteria that many manufacturers look for when selecting a lead solder substitute are the application temperature which is based on the melting temperature of an alloy, and the specific elements in the alloy system. Dr. Jennie S. Hwang is a leading expert in the field of lead-free solder research. She has published many articles and books on alternatives for lead solder which include the following. (Hwang, 2000)

If a melting temperature of less than 205ºC without the presence of Bi is desired, Alloy 370 (88.5Sn/3Ag/0.5Cu/8In) and Alloy 348 (87.4Sn/4.1Ag/0.5Cu/8In) in the Sn/Ag/Cu/In family exhibit the best characteristics. Both of these alloys possess a much higher tensile flow stress than 63Sn/37Pb and the plastic strain at fracture is nearly equal.

If a melting temperature of less than 215ºC without the presence of In is desired, the optimal lead-free solder choice goes to 93.3Sn/3.1Ag/3.1Bi/0.5Cu from the Sn/Ag/Bi/Cu family. It has a melting temperature ranging from 209º to 212ºC and offers higher strength with a significant plasticity as well as fatigue resistance higher than 63Sn/37Pb.

If a melting temperature of less than 215ºC without the presence of Cu is desired, Alloy AC (90Sn/3.3Ag/3Bi/3.7In) is considered to be the best substitute at this time. It has superior strength with a sufficient plasticity and a fatigue resistance higher than 63Sn/37Pb. The melting temperature of Alloy AC is between 206º to 211ºC and wetting characteristics are suitable for consideration as a replacement for 63Sn/37Pb.

If a melting temperature of less than 215ºC without the presence of Ag and Bi is desired, Alloy 719 (92.8Sn/0.7Cu/0.5Ga/6In) and Alloy 717 (93Sn/0.5Cu/0.5Ga/6In) in Sn/Cu/Ga/In system offers strength and fatigue life superior to 63Sn/37Pb. The fatigue life for Alloy 717 is 74 percent higher than 63Sn/37Pb and has melting temperatures ranging from 209º to 214ºC. Alloy 719 is 196 percent higher in fatigue life and exhibits melting temperatures between 210º to 215ºC. Both have wetting characteristics applicable for SMT manufacturing and integrated circuit packaging.

If a melting temperature of less than 215ºC without the presence of Cu and In is desired, Alloy 92Sn/3.3Ag/4.7Bi is considered as the optimal lead-free choice. This alloy has superior strength with a sufficient plasticity and an equivalent fatigue resistance to 63Sn/37Pb and the wetting characteristics are suitable for printed circuit board assemblies.

From the list of lead-free alloys above, it does not appear that there will be an ideal substitute for the more recognized eutectic tin-lead solder, 63Sn/37Pb. Depending on the application and specifications, industries will need to spend additional time to research for an appropriate substitute. Contract manufacturers will play a key part in assembling an accurate categorization for lead-free alloys. This is because of the many industries that contract manufacturers work with allowing for more diversity. The following table is provided as a guide for alloy selection and lists some known alloys and the industries served. (Shina, 2000)

Table 4.1 Alloy Selection Guide

ALLOYS USED	MELTING RANGE (ºC)	INDUSTRY SERVED	COMPANY
Sn/Ag	221 - 226	Automotive	Visteon (Ford)
Sn/Ag/Bi	206 - 213	Military/Aerospace	Panasonic
		Consumer	Hitachi
Sn/Ag/Bi/Cu		Military/Aerospace	Panasonic
Sn/Ag/Bi/Cu/Ge		Consumer	Sony
Sn/Ag/BiX	206 - 213	Consumer	Panasonic
Sn/Ag/Cu	217	Automotive	Panasonic
		Telecommunications	Nokia
			Nortel
			Panasonic
			Toshiba
Sn/Bi	138	Consumer	Panasonic
Sn/Cu	227	Consumer	Panasonic
		Telecommunications	Nortel
Sn/Zn	198.5	Consumer	NEC
			Panasonic
			Toshiba

4.2.2 Printed circuit boards

Having lead-free solder alone doesn’t eliminate the usage of lead. As stated earlier, the finishes on printed circuit boards have lead in them. It is important to protect the copper conductors on PCBs from degradation. This is why PCBs are applied with finishes via hot air solder leveling, electroless metals, and organic solder protectants. A completely lead-free electronic assembly will require that there be no lead in the finish. Therefore, board fabricators must select an alternative rated on cost, reliability, and shelf life.

- Organic Solder Protectants (OSPs) – OSPs are a viable candidate because they are almost in the same price range as tin-lead (about 25 cents/sq. ft) and contain no lead. These finishes are also processed easily, relatively free of ionic contaminants, and are smoother than HASL. They also have good solderability and are reworkable.
- Lead-free Hot Air Solder Level (HASL) – even though lead-free HASL is available for PCBs, some manufacturers may choose to move away from this process if required to produce lead-free product. Even though 70% of the PCBs currently produced worldwide are thought to be HASL finished, problems such as flatness of the finish make it difficult to mount small components.

  Alternative HASL finishes will most likely work well with most alternative alloys and will wet faster than plated finishes or coatings. However, there are concerns with this finish include warping due to higher processing temperatures and PCB absorbed process chemistries. These absorbed chemistries can sometimes be removed with cleaning.

- Immersion Finishes – Immersion finishes have been considered as replacement for HASL because of its surface flatness and ease of process. Concerns must be addressed regarding the thinness of the coating, because higher soldering temperatures could result in out-diffusion of base metals and oxidation, leading to reduced solderability.
- Electroless NiAu (Electroless Nickel Immersion Gold) – These finishes are attractive because of their resistance to damage during handling/processing and improved shelf life over other finishes. These finishes are also free of ionic contaminants, compatible with most flux chemistries, and smoother than HASL.

The following table shows usage of different surface finishes and their market trend. (Shina, 2000)

Table 4.2 PCB Surface Finish Trends

Final Metallic Finish	1997	1998	1998 est.	1999 est.
Copper Only (OSP)	28.2%	19.1%	30.0%	21.4%
Selective Solder Coat (HASL)	59.7%	67.8%	56.8%	68.3%
Tin-Lead Plate and Re-flow	5.0%	2.7%	3.6%	1.4%
Tin	0.1%	0.1%	0.2%	0.1%
Nickel-Gold	5.8%	4.2%	7.0%	3.8%
Immersion Gold	-----	4.1%	-----	3.7%
Palladium	1.0%	1.3%	2.1%	0.8%
Tin-Nickel	0.2%	0.4%	0.2%	0.2%
Other	0.1%	0.2%	0.1%	0.1%
Total	100%	100%	100%	100%

4.2.3 Electronic components

Several types of lead-free component finishes are available to the industry and have been successfully used in assembly operations. There are concerns over cost, reliability, and workability with lead-free alloys due to factors such as higher melting temperatures. For those manufacturers who choose to use components with a lead bearing finish, there is the concern with fillet lifting resulting from the use of some lead-free alloys. Although the fillet lifting does not occur in all circumstances of throughhole or surface mounting applications, it is an important consideration for companies in deciding whether to use alternative component finishes.

The most common alloy used in component finishes is palladium, which is usually used with nickel, silver or as a stand-alone finish. Some other concerns expressed by industry include re-qualification that may be needed for temperature sensitive components.

With molded components come concerns with delimitation and the time needed to define new materials and that temperature sensitive components may need time for re-qualification and redesign. There is a growing concern for the time needed to develop new molding compounds. The compounds developed to meet the higher temperature lead-free requirements should also meet the requirements of halogen-free materials. The following table lists some molded component surface finishes and their concerns. (Shina, 2000)

Table 4.3 Molded Component Surface Finishes

Finish	Manufacturing Experience	Concerns
NiPd	Yes	Material cost (Process is cheaper; must switch 100%)
NiPdAu	Yes	Material cost
SnBi	No	The assembly must be totally Pb free
Sn	Yes	Tin whiskers
SnCu	Yes	Tin whiskers

One resolution for BGA, CSP, and TBGA applications seems to be the use of balls formed with solder from the SnAgCu family. If this path is chosen, concerns need to be addressed regarding the affects of high-temperature solders on the substrate and warping of BGAs. One must also have an understanding of the intermetallics and shear strength of balls made with new materials.

Flip chips are internal to a package. This is the reason why there is no known solution for flip chip applications due to the temperature hierarchy. In the case of direct chip attach, there is a proposal for the use of patented indium solder or one compatible with the SnAgCu family, which is limited to small die. Based on these facts, a proposal is considered for exemption of these components.

Materials for connectors and throughhole components will be the same as those for molded components. The one concern for these components is warping under higher melting temperatures, but more data is necessary before making specific determinations on these applications.

4.3 Lead-free manufacturing

How will substituting materials that have lead with lead-free materials affect the machines being used? The behavior of lead-free materials as described above is quite different from lead-based materials. The machines being used must be capable of consistently handling these differences in behavior. This might require the purchase of new equipment.

4.3.1 Stencil printer

Stencil apertures must be cut to provide for sufficient solder coverage. Too much solder might result in bridges while insufficient solder might leave opens. A case study was conducted by researchers at Flextronics International Limited. (Yi, 2000) One goal of the research was to determine whether there are differences between the printing ability of lead-based and lead-free solders. The test vehicle used included components with lead pitches ranging from 0.3mm to 0.6mm and stencil aperture openings ranging from 6mils to 16mils. The alloy family used in comparison to the standard 63Sn/37Pb was the Sn/Ag/Cu family. The settings for the stencil printer were as follows:

- Printing pressure = High
- Printing speed = Low
- Squeegee separation speed = Medium

In the screen printing process, few differences were found between lead-free solder pastes and tin-lead solder pastes. It was observed that some of the lead-free solder pastes printed easier that their tin-lead counterparts with respect to print quality and snap-off. With respect to component placement, lead-free solder pastes and tin-lead solder were equivalent in performance. They both exhibited the same level of tackiness. Overall, tests revealed little differences between leaded and lead-free solders when screened with a stencil printer.

4.3.2 Pick and place machine

The function of pick and place machines, on the whole, will remain the same. These machines are used to pick electrical components from feeders and then place them onto solder pasted printed circuit board pads. The reason they remain the same is that the issue of lead doesn't affect the performance of these machines. Furthermore, there are no characteristics of lead that need to be controlled by these machines. The role of these machines is primarily moving components from one place to another. Therefore, manufacturers will not need to worry much about redesigning the use of these machines.

4.3.3 Reflow oven

The Flextronics study also took a look at the lead-free reflow process window. An alloy of Sn/Ag/Cu with a melting point temperature of 235ºC was tested at three different peak temperatures. The peak temperatures used were 220ºC, 235ºC and 245ºC.

At the peak temperature of 245ºC, which is higher than the recommendation, the dull solder joint and dark color residue was formed. This shows that the peak temperature of 245ºC may be too high and caused the flux residue to be slightly burnt.

At the peak temperature of 220ºC, which is lower than the recommended peak temperature and only a few degrees higher than the melting temperature, the solder joint surface is rough and the wetting area is insufficient. This indicates that the solder paste had not been completely reflowed due to low peak temperature.

At the peak temperature of 235ºC, which is the recommended peak temperature by paste vendor, solder joint is shinier and flux residue is clearer as compared with the joint under peak temperature of 245ºC and 220ºC. The results of the study concluded that even though the reflow peak temperature range of ±10ºC is common for tin-lead solder, it was not suitable for lead-free solder.

Although most lead solder alternatives require higher melting temperatures, most reflow ovens have the capacity to maintain these temperatures. The newest oven configurations enable manufacturers to optimize reflow for the entire range of pastes and profiles. Such systems are already in use by numerous major assembly companies and are available to all manufacturers.

4.3.4 Cleaning

Lead-free alloys require higher levels of activator to remove oxides and to properly wet the surface. As a result, the process window for lead-free soldering is narrower than eutectic tin-lead. Alloys containing high tin levels require more aggressive flux formulations. Their residues will be more intense, darker and increasingly difficult to remove

Regardless whether cleaning is performed at the assembly stage, the finished assembly must not contain residues that could result in premature field failures. If cleaning is not performed at the assembly stage, the incoming parts must be free of potentially harmful residues. Also, contamination must not occur during hand soldering or repair.

Cleaning requirements and defluxing ease start with the soldering operation's nature and the components to be assembled. Normally a foamed-fluxed, through-hole wave soldered assembly would be expected to be easier to clean than a high-density, fine-pitch surface mount assembly. The more aggressive the flux and the tighter the spacing between leads or tracings, the greater the cleanliness degree required.

In addition to the ability to deflux, choosing cleaning media and equipment is determined by numerous factors. Apart from its main job, the system also must meet economic, worker safety and environmental considerations. Local volatile organic compound emissions could determine the cleaning media choice and equipment. Similarly, wastewater regulations may require low-biochemical oxygen demand cleaning media. If an assembler cannot safely store and handle flammable materials, nonflammable media would be the preferred choice. Additionally, the cleaning agent must be compatible with the assembly materials and the washing equipment.

4.4 Rework

The Electronics Manufacturing Productivity Facility (EMPF) in Philadelphia, Pennsylvania conducted studies in lead-free implementation. Among the studies performed was a study on hand soldering issues. EMPF performed trials with lead-free hand soldering with the objective being to determine the differences between using lead-free solders and tin-lead solders. It was determined that the solder tip temperatures were higher. Generally speaking, the solder tip temperature required was above 650ºF (343ºC) for lead-free versus 600ºF (315ºC) for tin-lead. In order to achieve the same solder joint, the soldering iron must remain on the solder joint longer, prolonging the dwell time to promote adequate heat transfer to the hardware. However, the soldering iron must be removed quickly to avoid creating icicles on the solder joint. Operators must be more diligent in assuring that their soldering irons are clean when using lead-free solders as opposed to tin-lead solder. Lead-free solders are more sensitive to dirty solder tips than their tin-lead counterparts, probably due to the higher solder temperatures employed.

4.5 Inspection

Visual inspection by quality control personnel and optical inspection machines will require new training as the appearance of lead-free solder joints are different from leaded solders. Lead-free solder joints have a more grainy appearance while leaded solders are brighter and shinier. Board finish affects the solder joint appearance more easily with lead-free than with tin-lead solders. However, studies done at the American Competitiveness Institute in Philadelphia, PA found that HASL and NiAu finished boards do present brighter solder joints with good wetting while OSP finishes yielded poor wetting and required additional process development before being used. Furthermore, a nitrogen, reflow soldering atmosphere improved solderability, leaving brighter solder joints with less visible residue than those soldered in air.

Given the potential for different types of solder joint appearances, additional training will be needed in order to identify the different processes and materials used with the resulting solder joint appearance. If the appearance is grainy compared to shiny, then the inspection will need to be specified accordingly. Once again, the contract manufacturing industry will play a key part in the development of such a database while OEMs tend to focus on a primary product line.

4.6 Summary

Lead-free manufacturing will not force manufacturers to spend large sums of money on new and expensive equipment. The reflow oven is the only machine that will need considerable change in performance due to higher solder melting temperatures. Most reflow ovens will be able to handle these temperatures. However, manufacturers will be forced to research and understand the various types of lead-free solders, components, and PCB finishes currently available to the industry.

The attributes of a lead-free system that are most important begin to appear after the lead-free materials pass the pick and place station through the reflow oven. The selection of solder alloys combined with PCB surface finishes is critical for the best connectivity between the components and the PCB. Certain components will not be capable of maintaining stability through higher reflow temperatures. For these, additional processes will need to be considered.

The different combinations of materials will affect the appearance of the solder joints. This will affect the way inspection is currently done. Human as well as optical machines will require new training in order to provide the best inspection results. Another area where training will be needed is rework. Higher solder melting temperatures will require higher soldering iron temperatures. Careful attention must be used in order to maintain adequate heat from the soldering iron because lead-free solders tend to be more sensitive due to higher temperatures.

For contract manufacturers, a lead-free implementation will provide them with a number of benefits. The most important benefit is the manufacturer will be eliminating a known toxin, lead, from the workplace and the environment. The history of lead speaks clearly for itself about the potential dangers that could emerge in the future if lead continues to be used. The dangers of lead in the workplace will no longer exist. Without lead, manufacturers will no longer need to worry about potential government legislation either.

With the rest of the world quickly shifting to lead-free, an implementation to lead-free will provide manufacturers with a competitive edge as well. Since electronics manufacturing is a global industry, international partnership can stay intact. Aside from competitiveness, manufacturers can begin building their own libraries of alloys and materials. Lead-free will require much more training and experience for all production personnel. Regardless, lead-free is on its way. It would be beneficial for a manufacturer to keep up with technology as it moves into lead-free.

Since lead-free is coming, a simple implementation plan needs to be established. The following is a simplified model for lead-free implementation:

1. Manufacturers must first survey all approved material vendors. The survey should include questions regarding the vendor’s current lead-free status, available inventory, costs, and lead times. This will provide the manufacturers with an idea of what is available and whether it is possible to implement lead-free. Surveying beyond the approved vendor list might be needed depending on the results of the initial survey.
2. Sample runs should be done next. Dummy components and PCBs are readily available for testing purposes. During this step, statistical analysis can be done with the various types of materials used with emphasis on more critical elements. Careful consideration does not have to be paid to machines like the stencil printer and pick and place because they are not affected by the use of lead-free materials. Profiling the reflow oven and optical inspections will require additional time.
3. Training should be provided for quality inspectors and optical inspection machine operators.

With regards to contract manufacturers, the selection of materials will not be an issue. Most of the time, the customer will specify the materials to use. However, the manufacturer should still have ample knowledge of materials in the cases where design is an issue and the customer may request recommendations.

CHAPTER V

CONCLUSIONS

5.1 Conclusions

Whether or not US manufacturers want to consider lead-free alternatives is no a topic of debate. It is now when manufacturers want to implement lead-free into their current processes. Lead-free manufacturing is coming. Safety and health concerns, legislation, and global competitiveness are its main drivers. Manufacturers will need to invest in adequate planning for lead-free and consider the critical elements of a lead-free implementation. They will need to gain a better understanding of the materials, machines, and methods that will be impacted the most with a lead-free implementation in order to maintain success.

Materials

There are a variety of lead-free solder alloys to choose from with each having different characteristics depending on the application desired. The availability of technical information on each alloy increases as the industry continues to research and adopt lead-free alloys. The main factors in selecting the appropriate lead-free solder alloy are the melting temperature of the solder and the cost of the alloy. As the industry's database of alloys continues to grow, the process of solder selection will become more exact. Ultimately, a collection of standard alloys will emerge.

Several PCB finishing techniques are available for manufacturers with OSP being the most applicable to lead-free solders. However, the technology surrounding lead-free continues to evolve. Board finishes will also emerge with a few standard methods compatible with most alloys. As with solders, board finishes will not have a eutectic type due to many types of alloys of solder available. Selection of materials will be critical due to higher solder temperatures. Component integrity must be maintained.

Machines

The stencil printer studies done by Flextronics concluded that there is no significant difference in performance between lead and lead-free solders. Manufacturers can expect to find little difference in processing through the stencil printer with lead-free solders. On the same note, pick and place machines will also remain relatively the same. The fact is that the role of pick and place machines is essentially taking a component and placing it onto a pad. Regardless of the type of solder used, the function of this machine will remain the same.

The higher melting temperatures of lead-free solders will demand higher performance from reflow ovens. Most ovens will have the capacity to meet or exceed these temperatures without much wear and tear to the machine over time. Profiling will require more knowledge of the many different alloys increasing the number of profiles available to a manufacturer.

Methods

Depending on the combination of solder, board finish, and component, the surface finish of the solder joint will not be the same. The appearance of the solder joint will range from dull - shiny with the different combinations. Visual inspectors will require special training on differentiating between the kinds of solder joints to expect. Optical inspection machines will also need to be programmed with the mindset that varying finishes will be produced.

5.2 Recommendations

The steps to implementation outlined in the previous chapter serves as a basic model for manufacturers to follow. Information gathered from vendors will provide a better picture as to whether implementation is possible. Sample runs will help manufacturers fine tune their process capabilities. These steps will help the manufacturer to stay ahead of potential legislation and allow a successful lead-free implementation when needed.

5.3 Future studies

- Availability of lead-free materials – additional research is needed to determine if lead-free substitutes are readily available to US manufacturers at a reasonable cost. This will contribute to a future cost analysis study.
- Cost analysis – additional research is needed to determine the cost associated with lead-free manufacturing.

- Trace ability of alloys – additional research is needed to determine how the many types of alloys will be tracked once the product leaves the manufacturing plant.

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