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LEAD-FREE SOLDERING PROCESSES IN THE ELECTRONIC INDUSTRY – INDUSTRIAL IMPLEMENTATION AT SMES

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ABSTRACT: Following the implementation of the new European environmental directives, Restriction of the Use of Certain Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE), which involve the ban of lead from electronic and electrical products, this work presents process development work, production and reliability testing of real products from several electric and electronic assemblers using lead-free commercial solders that have been tested and monitored to ensure the reliability of the final products. The results were compared with the ones using tin/lead solders, in terms of performance and reliability of the joints obtained. This work aims to help the implementation of the lead-free solders in the soldering processes and supply the SMEs more information about real products and conditions that might be compared with theirs.

The reliability tests and characterisation of the real products from several companies showed that the lead-free boards demonstrated a good performance under testing, being equivalent or better than the tin/lead ones. The defects or anomalies found in most of the joints (voiding and pad lifting) result from the manufacturing process. Most of the defects were found in through-hole devices and were due to component failures and not from the joint integrity. The degradation after the reliability tests of both types of solders is similar.

The SMEs are engaged in taking this opportunity to reach a higher quality performance level in their processes. Some of the companies embraced this "forced" transition to upgrade and improve their process and facilities, bringing better capabilities and opportunities to their businesses.

The objective of this work aims to be a tool of information to the SMEs of the electrical and electronic sector, in order to help them in the transition to lead-free soldering.

Keywords: Lead-free solder, Soldering, Electronics, Reliability, PCB, RoHS.

RESUMO: No decorrer da implementação das recentes directivas ambientais Europeias: Restrição do Uso de Substâncias Perigosas (RUSP) e Resíduos de Equipamentos Eléctricos e Electrónicos (REEE) surge a proibição do uso de chumbo em produtos eléctricos e electrónicos. Este trabalho apresenta o estudo de desenvolvimento de processo, produção e testes de fiabilidade em produtos reais de diversas empresas do sector eléctrico e electrónico. Vários tipos de soldas comerciais foram usadas e testadas de modo a permitir a comparação em termos de performance das soldas sem chumbo face às com chumbo. O presente trabalho tem como objectivo o apoio às PMEs (Pequenas e Médias Empresas) durante a implementação da soldadura sem chumbo nos seus processos industriais e fornecer-lhes mais informação sobre produtos reais que lhes permita comparar com a sua própria produção.

Os testes de fiabilidade e a caracterização feita nos produtos em estudo demonstraram que as placas soldadas sem chumbo possuem uma boa performance em teste e são equivalentes ou superiores às placas soldadas com soldas com chumbo. Os defeitos e anomalias encontradas nas juntas soldadas resultam, essencialmente, do processo de fabrico e não das pastas e soldas utilizadas. Na sua maioria, as falhas encontradas nas placas são devidas a falha de componentes e não da integridade das juntas. A degradação das soldas após teste é similar nos dois tipos de solda.

As PMEs estão motivadas em aproveitar esta transição "forçada" para melhorar as suas capacidades, equipamentos, processo e oportunidades de negócio.

O objectivo final deste trabalho é fornecer informação às PMEs do sector eléctrico e electrónico, de modo a apoiar a sua transição para a soldadura sem chumbo.

Palavras chave: Solda sem chumbo, Soldadura, Electrónica, Fiabilidade, PCB, RUSP.

1. Introduction

1.1 Objectives

This work results from the implementation of the new European environmental directives, particularly the Restriction of the Use of Certain Hazardous Substances (RoHS). From all the restrictions imposed by the Restriction of the Use of Certain Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) directives, banning of lead from electronic and electrical products had one of the biggest impacts on this industrial sector (see sub-chapters 2.1.1 and 2.1.2). Small and Medium Enterprises (SME) that have to strive with the huge competitiveness of the market are now facing a new obstacle, the substitution of solder alloys and all the consequences that this change implies.

This work presents process development work, production and reliability testing of real products from several partners with commercial solders that have been tested and monitored to ensure the required reliability of the new lead-free solders and compare them with the previous lead containing ones. It aims to help the implementation of the lead-free solders in the soldering processes and supply to the SMEs more information about real products and conditions that might be compared with theirs, and not only results obtained from ideal conditions as in the laboratory. Finally the objective of this work is to be a tool of information to the SMEs of the electrical and electronic sector, in order to help them in the transition to lead-free soldering.

1.2 Workplan

The present work is based in an industrial research project and compiles in a brief manner several of the main results obtained with electric and electronic industrial assemblers from Portugal, Spain and United Kingdom. The first part of this work brings an analysis of the European directives and their impact in industry, and some information about the basic principles of soldering in electronics. A description of the work carried out and results are presented in the second part. Finally the economical and environmental impacts are evaluated, and the discussion and conclusions of the work is presented. Several industrial products were selected from each of the industrial partners for the work presented in the second part of this thesis. These products were manufactured and all data recorded, including the level of the defects found for each type of solder tested. The boards were visually inspected before and after the reliability and functionality tested. Some joints from each board were then selected and characterised by optical and electronic microscopy.

2. Electronic industry issues related to European directives

2.1 European directives

2.1.1 RoHS

The Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment – RoHS Directive – implements the provisions of the European Parliament and Council under the Directive 2002/95/EC. The RoHS Directive bans the introduction on the EU market of new Electrical and Electronic Equipment (EEE) containing more than the permitted levels of lead, cadmium, mercury, hexavalent chromium and both polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants from 1st July 2006. Manufacturers will need to ensure that their products - components and sub-assemblies of such products - comply with the requirements of the RoHS Directive. [1, 2]

2.1.2 WEEE

The Waste Electrical and Electronic Equipment Directive (WEEE Directive) is the European Community Directive 2002/96/EC on waste electrical and electronic equipment. The purpose of this directive is the prevention of WEEE, and in addition, to regulate/stimulate the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste [3]. The directive imposes the responsibility for the disposal of WEEE on the manufacturers of such equipment. Those companies should establish an infrastructure for collecting WEEE, in such a way that "Users of electrical and electronic equipment from private households should have the possibility of returning WEEE at least free of charge". Also, the companies are compelled to use the collected waste in an ecological-friendly manner, either by ecological disposal or by reuse/refurbishment of the collected WEEE. [4, 5]

2.2 Lead-free industrial implementation concerns

The main issue that comes from the prohibition of lead alloy solders is the increase of the melting point that is inherent to the alternative solders. This increase of the melting point of the solders has several important implications to the manufacturing process. Surveys were carried out before the implementation of the RoHS directive to the electric and electronic industry participating in the project, in order to investigate their concerns and possible problems. The results showed that the main concerns were related to [6]:

- Investment in new equipment or upgrades;
- Thermal limitations of some components and materials;
- Thermal profile and temperatures to be used;
- Low cost reliable solders;
- Reliability of the products;
- Bath contamination on wave soldering;
- Solderability on rework process;
- Differences in the joint appearance that has a great impact in inspection.

Some of these concerns have become a reality with the transition to the lead-free process, others have been overcome or even not found at all, e.g. decrease of the products reliability under single standard tests. A lot of work has been done in this area and a lot more still has to be done, not only to achieve the implementation of the directives but to take the electric and electronic sector to another level.

3. Soldering in electronics

3.1 Basic principles of soldering

Soldering is one of the oldest processes that use melting to join two metals. It is defined to be all the joining processes that do not melt the base material, the joint is produced by heating and adding another metallic alloy, which melting point is lower than the "solidus" temperature of the base material. The alloy penetrates the joint, filling it, by capillarity [7]. Efficient functioning of electrical and electronic equipment is in many ways dependent on the correct interconnection of electrical components. This interconnection relies to the most part on soldering.

In electronics, Printed Circuit Boards (PCB) are commonly used to mechanically support and electrically connect electronic components using conductive copper paths laminated onto a non conductive substrate. Some PCB's are composed of one up to more than twenty-four conductive layers separated by other layers of insulating material laminated together. The conductive layers are almost invariably made of copper in all types of boards [8]. Layers may be connected together through drilled holes (vias), to form an electrical connection. These vias can be electroplated or alternately small rivets can be inserted. In every PCB small copper traces or tracks are visible on the surface, these traces are made by adhering a layer of copper over the entire substrate and then removing the unwanted copper by etching, using a mask, leaving only the desired copper traces. Pads to which components will be mounted are normally plated, because bare copper oxidizes quickly, reducing solderabillity. Platings like OSP (organic surface preservative), Immersion silver and ENIG (electroless nickel with immersion gold) are used [9].

3.1.1 Thermal aspects

In soldering one of the most important parameters is the soldering temperature (T_{sd}). As regarding T_{sd} there is a dilemma: the parts to be soldered should be heated to a temperature high enough to be wetted by the solder but on the other hand, the temperature that the components suffer during the assembly process should not be so high that can affect their operating characteristics. This issue has become more problematic with the introduction of lead-free solders. The components have to withstand temperatures higher than 217ºC (lead-free solder melting point), instead of 183ºC (lead solder melting point) with the eutectic tin/lead solders. Some components are not prepared for this process changeover and cannot stand the higher temperature demands (Fig. 1).

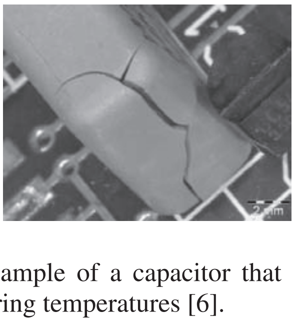

Figure 1 – Example of a capacitor that was not suited to lead-free soldering temperatures [6].

Each component has its size, geometry, heat capacity and other characteristics that should be kept in mind. To achieve a good solderability over the whole board a well designed temperature profile has to be used, especially with lead-free and the consequent decrease of the process window. The process window ΔT changed from 40-45ºC to 10-15ºC leaving almost no margin between the melting point and the damaging point [8]. Lead-free solder have smaller process windows because the temperatures of the reflow soldering process are basically determined by the melting point of the solder alloy. For adequate soldering, every point in the board has to reach at least the melting point of the alloy. This means that we have to deliver at least 20ºC higher than the melting point for even distribution of temperatures. On the other hand, components have a maximum temperature that they can endure without damage. Thus, in the lead-free solders with higher soldering temperature the gap to max component temperature is decreased [6].

Pre-heating is very important in all lead-free soldering processes in order to facilitate wetting, reduce contact time, prevent thermal shock from room temperature to soldering temperature and to activate the flux agent [8]. To avoid the thermal differences in the board pre-heat should be use in all processes (reflow, wave, selective soldering…). Temperature profiling is essential in order to assure that the peak temperatures of the components are not being compromised. Using a set of thermocouples attached on the boards can give valuable information about the temperatures distribution among board, components and solder. This is an excellent tool for setting up the process.

3.2 Fluxes

One of the primary purposes of fluxes is to prevent oxidation in the base material (substrate). Solders can attach very well to copper (Cu), but poorly if copper oxide is present, which form quickly at high temperatures. Fluxes are to a large extent inert at room temperature, but become strongly reducing at high temperatures, mitigating the formation of metal oxides. The second objective of fluxes is to act as a wetting agent in the soldering process, increasing the surface tension of the substrate and promote wettability. And the third objective is to aid the heat transfer to the joint area [8].

3.3 Solder Alloys

3.3.1 Alloys

Lead containing solders have been used extensively in microelectronic applications to form electrical interconnections between packaging levels, to facilitate heat dissipation, to provide mechanical/physical support and to serve as a solderable surface finish layer on PCB's and lead frames [10]. This wide use of lead containing solders is due to the low melting point of the tin (Sn)/lead (Pb) alloy (183ºC), good wettability, good mechanical and electrical properties, and relative low cost.

As mentioned before, due to European restrictions lead has been banned from solder alloys and a new era has begun. The demand for new lead-free alloys was a priority concern and several alloys were tested and are currently being experimented. In the following table some examples of solder alloys commercially used are presented:

Table 1 – Examples of commercial solder alloys compositions and their melting points [6].

Solder	Alloy	Melting Point (ºC)
Lead	63Sn/37Pb	183
	60Sn/40Pb	183-187
	62Sn/36Pb/2Ag	179
Lead-free	96.5Sn/3.5Ag	221
	99.3Sn/0.7Cu	227
	96.3Sn/3.2Ag/0.5Cu	217-218
	96Sn/3.8Ag/0.7Cu	218

3.3.2 Metallurgy

Lead alloys

Alloys of this simple eutectic system are composed of primary dendrites of either tin-rich or lead-rich solid solution surrounded by eutectic. The eutectic occurs at 61.9% tin (183ºC) and consists of lead-rich and tin-rich phases either lamellae or globules, depending on the solidification rate. The higher the solidification rate the greater the probability of formation of a globular eutectic. These solders have relatively fast solid state reactions with other elements such as copper, leading to the formation of intermetallic compounds in the vicinity of the solder. The molten eutectic tin/lead solder during solidification separates into two different solids, a lead-rich phase and a tin-rich phase.

Sn/Ag/Cu alloys

Tin/silver eutectic formation is very important for lead-free solders in electronic industry. The eutectic composition for this alloy is located at 96.5 wt% (Sn) and 3.5 wt% (Ag), with a melting point of 221ºC. During solidification, when the temperature reaches below the eutectic tie-line, the (Sn) solid phase and γ intermediate phase form heterogeneously together from the liquid (L).

$$L(96.5\%Sn)\xrightarrow{221^{\circ}C}\beta-Sn(100\%Sn)+\gamma(73.2\%Sn) \qquad (1)$$

As the (Sn) phase grows, the excess (Ag) atoms in the liquid are rejected from the tips of the (Sn) phase, and will diffuse laterally in a short distance to the γ phase (Ag_3Sn). On the other hand, the excess of (Sn) atoms rejected from the γ phase will diffuse to the tips of the near (Sn) phase. The (Sn) phase in the eutectic composition 96.5 Sn/3.5 Ag predominates over the γ phase; the (Ag) solute is dissolved in the (Sn) phase due to the longer distance to the γ phase. The (Ag) enrichment in the liquid (the ones that do not incorporate the γ phase) may cause constitutive super-cooling and lead to the formation to dendrites, with γ phase growing between the dendrite arms.

Another important eutectic formation for the solder alloys is the tin/copper eutectic. This eutectic is located at 99.3 wt% (Sn) and 0.7 wt% (Cu) with a melting point of 227ºC. As previously discussed, this alloy also has a eutectic transformation similar to the Sn/Ag eutectic.

$$L(99\%Sn)\xrightarrow{227^{\circ}C}\beta-Sn(100\%Sn)+\eta(60.9\%Sn) \qquad (2)$$

The η corresponds to the Cu_6Sn_5 phase at 45.45 at% (Sn). There are two possible binary eutectic reactions in the Sn-rich region of the ternary system Sn/Ag/Cu. These reactions are shown in the circle on the ternary phase diagram of figure 2. Copper reacts with (Sn) to form a eutectic structure of Sn-matrix phase and η intermetallic compound phase (Cu_6Sn_5) at 227ºC. A reaction between (Ag) and (Sn) forms a eutectic structure of Sn-matrix phase and γ intermetallic phase (Ag_3Sn) at 221ºC. Finally, (Sn) solidifies in the end leading to the ternary invariant eutectic point U_7. (Ag) also reacts with (Cu) to form a eutectic structure of Ag-rich α phase and Cu-rich α phase at 779ºC. However, this transformation is not detected in the solidification, is thermodynamically favourable for (Ag) or (Cu) to react with (Sn) to form the presented intermetallic compounds. The ternary solder alloy Sn/Ag/Cu consists of a Sn-matrix phase, γ intermetallic phase (Ag_3Sn) and η intermetallic compound phase (Cu_6Sn_5) [11].

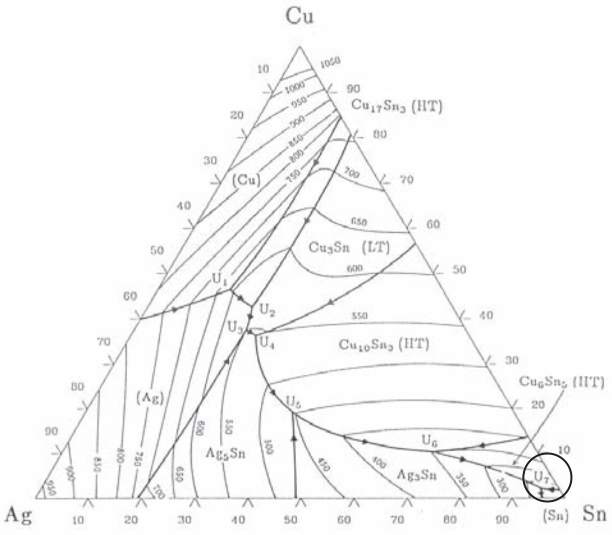

Figure 2 – Tin/silver/copper ternary phase diagram [12].

In terms of mechanical behaviour, in the Sn/Ag/Cu solders the thermomechanical strains will concentrate near the pad interfaces creating regions of high plastic deformation. In these regions the (Sn) phase will recrystallise above room temperature, producing fine grains that are more susceptible to creep deformation (grain boundary sliding or cracking) than the initial microstructure. Thus, providing an easy path for crack propagation during thermo cycles and decreasing the thermal fatigue life. In the Sn/Pb solders the fractures appear on the same locations but due to the microstructural coarsening of the (Sn) and (Pb) phases near the interface, leading to a local softening and to fatigue crack propagation [10].

3.3.3 Intermetallics

In the soldering process there are interfacial reactions between two different materials. When the solder touches the pad, two reactions take place at the interface solder/base material (joint):

- Dissolution of the base material into the molten solder;
- Formation of an interfacial reaction product, consisting of one or more elements from each of the solder and base material compositions.

An intermetallic compound is one type of intermediate phase that is a solid solution with intermediate ranges of composition. Intermetallic compounds may form when two metal elements have a limited mutual solubility. These compounds possess new compositions of a certain stoichiometric ratio of the two component elements for a binary system. The new phases have different crystal structures from those of their elemental components. The properties of the resulting intermetallic compound generally differ from those of the component metal, exhibiting fewer metallic characteristics, such as reduced ductility, reduced density and reduced conductivity [11].

The relatively hard Ag_3Sn and Cu_6Sn_5 particles in the Sn-matrix of Sn/Ag/Cu alloys can strengthen the alloy through the building of long-range internal stress. These hard particles can also serve as the most effective blocks for fatigue crack propagation. The formation of these particles can lead to finer grains, the finer the intermetallic particles are, the finer the microstructure will be. This facilitates the grain boundary gliding mechanisms leading to extended fatigue lifetime under elevated temperatures. The thin intermetallic layers provide the necessary permanent bond with the substrate, acting as "fixation phase". However, if the intermetallic layers become thicker the mechanical properties of the solder joint will weaken, due to the brittle nature of the compounds and to the difference of the thermal expansion between the intermetallics and the bulk solder. This can lead to internal stress development, resulting in crack formation along the solder/substrate interface. Optimum thickness is expected to be in the range of 1 to 5 micron [11]. A nickel barrier can be applied over the copper substrate to control the (Cu) dissolution and intermetallic compound growth. This will lead to different reactions. If the (Cu) pads are protected will an OSP coating, this one will vaporize on reflow allowing the solder to touch the bare (Cu) and form the intermetallics described above. When the pads are protected with an ENIG (electroless nickel/immersion gold) finish, the (Au) gold dissolves and migrates into the solder promoting the intermetallic layer formation between (Sn) and (Ni) – Ni_3Sn_4 or ternaries $(Cu, Ni)_3Sn$, $(Cu, Ni)_6Sn_5$. Literature presents the following relationships [13]:

- Hardness ($HV_{0.2}$: GPa) - $(Cu, Ni)_3Sn$ (5.5) > $(Cu, Ni)_6Sn_5$ (4.9) > Cu_6Sn_5 (4.6) > Ni_3Sn_4 (4.3) > Ag_3Sn (1.4).
- Poisson ratio - Ag_3Sn (0.35) > Cu_6Sn_5 (0.32) > $(Cu, Ni)_6Sn_5$ (0.30) > $(Cu, Ni)_3Sn$ (0.27) > Ni_3Sn_4 (0.27).
- Young's Modulus (GPa) - $(Cu, Ni)_3Sn$ (152) > $(Cu, Ni)_6Sn_5$ (100)> Ni_3Sn_4 (58)> Cu_6Sn_5 (57)> Ag_3Sn (55).

The Hardness and Young's Modulus for the Sn/Ag/Cu solder are 0.16 GPa and 50GPa, respectively. Ternary intermetallic compounds like $(Cu, Ni)_3Sn$ and $(Cu, Ni)_6Sn_5$ are hard and brittle but appear only on second reflows and are not usually observed. The Ag_3Sn, Cu_6Sn_5 and Ni_3Sn_4 (with (Ni) barrier present) are more common. From the relationships above, in comparison with the solder properties these intermetallics present harder and more brittle properties, which represent weaker zones in the structure. Due to its elongated plate-like shape, the A_3Sn presents more damage in case of excess. This intermetallic nucleates in front of the Cu_6Sn_5 layer and can grow rapidly during cooling. The structural differences between the (Sn) and Ag_3Sn will induce a strain at the boundary between them, leading to a preferential crack-propagation path, especially when the Ag_3Sn plates are aligned in the direction of the crack propagation [14, 15].

3.4 Industrial soldering processes

There are at least two steps that a board must undergo before the soldering stage: printing and component placement. Soldering processes can be divided in the methods that involve application of solder and heat simultaneously to the parts to be soldered like wave soldering, and the reflow method in which the solder and the heat are applied separately. In the reflow method the heat can be local (LASER, hot gas, hand soldering) or can be general (hot air convection, infra-red radiation, a combination of both, vapour phase) [8].

3.4.1 Reflow soldering

After the component placement on the pads (with the paste) the boards will move in a conveyor to the reflow machine (oven). The ovens produce heat by radiation through ceramic infra-red heaters, it may also have fans to force heated air to the assembly which is called infra-red convention ovens. Normally, the reflow ovens are divided in the following zones: pre-heat, soak, reflow and cooling, following the same stages of a temperature profile. Reflow ovens from 4 to 12 zones are available on the market.

3.4.2 Wave soldering

Wave soldering uses a pot with molten solder, the components are placed on the PCB and pass through a wave of solder, which is pumped from the pot. Wave soldering is used for both through-hole and surface mount printed circuit assemblies. For through-hole, the PCB touches the "cascade" of molten solder and by capillarity the solder rises through the holes and will form the joints. In the case of SMDs, the components are placed with adhesives on the PCB surface before being run through the molten solder wave. A standard wave solder machine consists of three zones: the fluxing zone, the pre-heating zone and the soldering zone. An additional zone, cleaning, can be used depending on the type of flux used [8].

3.5 Solder joints

3.5.1 Joint defects

Some of the examples that will be presented are not considered as defects by IPC-610-D Standard, but for simplifications purposes it shall be include this "abnormalities" in the defect section. The IPC-A-610-D standard presents acceptance requirements for the manufacture of electronic assemblies. It is a manual that includes detailed information, pictures and illustrations portraying what is or not expected to encounter on an electronic product [16]

The most common defects that can be found are described bellow:

Solder shorts

The boards and components are getting smaller, and with this also is the distance between components and terminations. This effect appears mostly in wave processes in which the solder does not separate from two or more leads before the solder solidifies creating a short. Increasing the flux quantity, optimise pre-heat, adjust process (speed) can help to mitigate this problem [17].

Solder balls

Solder balls on the topside of the board after reflow processes can be caused by the incompatibility between the solder resist and solder paste. Solder resist affects the mobility of the paste in the liquid state during reflow, as the paste reflows and coalesces, some small parts of the solder do not flow back to the joint (Fig. 3). It also can be due to poor flux pre-heating [17].

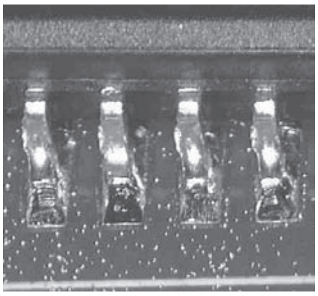

Figure 3 – Solder balls defect. [16]

Voids

Most of the voids are caused by moisture that becomes water vapour during the soldering process and expands, sometimes voids can come out of solder while the solder is in the liquid state, producing blow holes or non metallic material that is trapped in the printed board and it is not displaced during the soldering. Voids can be seen mostly on the base of the board because the solder solidifies firstly on the top and entraps them there. It reduces the joint strength but it is not necessarily a reliability issue, if not in excess. A good humidity storage control and baking the boards before soldering can eliminate the moisture [17]. Figure 4 shows an X-ray image of SOT23 (Small Outline Transistor) solder joints after reflow on a lead free production line, where it can be seen the voids in the solder.

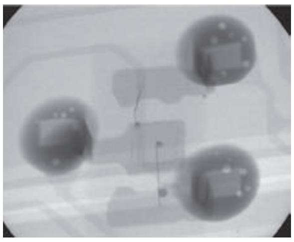

Figure 4 – X-Ray image of a SOT23 presenting voiding on all the joints [17].

Poor or incomplete filling

The hole is poorly filled or is not filled completely, the IPC standard states that 75% of the hole must be filled (Fig. 5). There are some possible reasons for this but the most common are fluxing and heating issues [17].

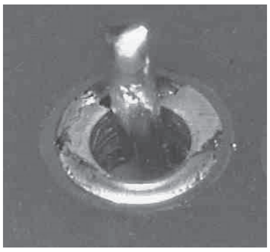

Figure 5 – Example of poor wetting defect. [16]

3.5.2 Inspection and characterisation techniques

The inspection and characterisation can be made through optical and/or electronic microscopy. The optical inspection is done through an optical microscope following the requisites of the standard IPC A-610-D class 3 and aims to determine the quality of the joints with respect to visual defects. The characterisation of solder joints implies the preparation of the samples for inspection. That process includes the micro-sectioning of the components, mounting in resin, grinding and polishing. Only then the sample is ready to be observed in the SEM (Scanning Electron Microscope). This equipment allows seeing all the internal and metallurgical defects present on the solder joint.

4. Lead-free process validation of commercial solders in industrial boards – Results overview

4.1 Introduction

In this chapter information is presented related with the boards that were studied as well as all the results extracted from the assembly process, visual inspection, reliability tests, optical and electronic microscopy of the sectioned samples. All the boards previously described were inspected and tested.

4.2 Soldering of industrial boards

Information about the boards used in the present work is briefly presented here:

Board A

This product, part of a video monitor unit, is a single sided through-hole circuit board, with both leaded and surface mount components. Surface mount components were placed on the board using reflow cured adhesive and then soldered along with the leaded components by wave soldering.

Table 2 – Summary of the board A soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Wave	63Sn/37Pb	No clean, rosin free Alpha Metals E191/1	250°C	OSP coated
Lead - Free				
Wave	SN100C Sn/Cu/Ni	Water-based, VOC free, spray DKL Metals E-Qual 355 flux	266°C (two waves)	OSP coated

Board B

This product, part of an intercom system used in theatres, is a single sided through-hole circuit board, with leaded components only.

Table 3 – Summary of the board B soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Hand	60Sn/40Pb	No-clean, rosin free, Interflux IF14 fluxed solder wire	350°C (iron tip)	Sn/Pb HASL
Lead - Free				
Wave	SN100C Sn/Cu/Ni	Water-based, VOC free, spray DKL Metals E-Qual flux	255°C (single wave)	Lead-free HASL

Board C

This product is an assembly that is used in door lock mechanisms in hotels. It has a reflow soldered, surface mount circuit board, with surface mount devices only.

Table 4 – Summary of the board C soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Reflow	62Sn/36Pb/2Ag	ROL0 no-clean Koki SE48-M955	-	Sn/Pb HASL
Lead - Free				
Reflow	96.5Sn/3.0Ag/0.5Cu	Koki Eco Plus S3X58-M406	-	Sn finish

Board D

This product is used in telephone systems as part of a call charging unit. The assembly has a double sided, plated through-hole, mixed technology circuit board, with both leaded and surface mount components on the top side only. Surface mount components were reflow soldered to the board, followed by wave soldering of the through-hole components.

Table 5 – Summary of the board D soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Reflow	62Sn/36Pb/2Ag	No-clean, Alpha Metals UP78-T	-	Au/Ni plated
Wave	60Sn/40Pb	No-clean, alcohol based flux; Multicore X33 12i	250°C	Au/Ni plated
Lead - Free				
Reflow	95.5Sn/3.8Ag/0.7Cu (4 boards) 96.5Sn/3.0Ag/0.5Cu (4 boards) 95.5Sn/3.8Ag/0.7Cu (8 boards)	Multicore LF310 Alpha metals OM338 Multicore LF318	-	Au/Ni plated
Wave	SN100C Sn/Cu/Ni	Hand–sprayed, no clean, alcohol based flux; Multicore X33 12i	270ºC	Au/Ni plated

Board E

This product is part of a Taxicab display sign. It has a double sided, plated through-hole circuit board, with both leaded and surface mount components. The through-hole components and surface mount chip resistors were assembled by wave soldering, the connector was hand soldered to the board.

Table 6 – Summary of the board E soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Wave	63Sn/37Pb	No-clean, rosin-free foam Kester 950E flux	250°C	Sn/Pb HASL
Lead - Free				
Wave	96.5Sn/3.0Ag/0.5Cu	No-clean, rosin-free, water based spray Warton Ecowave 45 flux	260°C	Lead-free HASL

Board F

This is a product used in digital display devices such as LCD monitors to improve the image quality. The assembly has a double sided, plated through-hole, mixed technology circuit board, with both leaded and surface mount components on the top side only. Surface mount components were reflow soldered to the board, followed by wave soldering of the through-hole components. The tin/lead through-hole components were attached using the lead-free process.

Table 7 – Summary of the board F soldering trials data.

Tin/Lead				
Process	**Alloy**	**Flux**	**Process Data**	**Board**
Reflow	63Sn/37Pb	No-clean, ROL0, Indium Corporation NC-SMQ-92J	-	ENIG
Lead - Free				
Reflow	96.5Sn/3.0Ag/0.5Cu	No-clean, Alpha Metals OM-338	-	ENIG
Wave	SACX Sn/Ag/Cu/Bi	No-clean, rosin based, sprayed Alpha Metals EF-6000 flux	260ºC	ENIG

4.3 Reliability tests

The objective of the reliability trials is to determine if there are significant differences in the performance between the conventional tin/lead and lead-free solder joints in the real products provided by the industrial assemblers. For this purpose some tests have been selected according to each product's requirements, in order to accelerate the stresses that solder joints will suffer in service. Several boards from each assembler were selected and submitted to various reliability tests, in table II-1 it is showed the distribution of boards to each test.

Table 8 - Summary of test standards and test methods

Test	Standard	Conditions
Visual inspection	Standard IPC-A-610-D	-
Low temperature storage	EN 60068-2-1Section 2. Test Ab	Conditions Temperature (-40°C) Duration 72 h
High temperature storage	EN 60068-2-2 Section 2. Test Bb	Temperature +100°C Duration 168 h or 672 h
Thermal cycling	IPC 9701 Cats 1,2 & 3 Test Condition 1 NTC level E	0°C to 100°C 3000 cycles or 6000 cycles
Mechanical shock	EN 60068-2-32 Part 2.1 Test Ed: Free Fall	1000 mm vertical drop steel surface. Number of falls 2
Thermal shock	Standard EN 60068-2-14 Part 2 Test Na (or Nb)	Conditions air to air temperature range (-40°C) to +100°C. 5 cycles, 3h/ 25 s/3h
Vibration	EN 60068-2-64	Random excitation: f1 =5Hz, f2 =1000 Hz Duration of exposure: 30 minutes Vibration axis: one each in the X, Y and Z directions
Component attachment strength	EN 60068-2-21 Test Ue3 Shear Test. Test Method 8.5.3.2	10N for 10s. Then destructive at 0.2mm/s

The assemblies were sent to the assemblers for electrical functional test before and after the reliability tests, the tests were selected in a way that may give information about the joints and their failure, and to avoid tests that can lead to failure in different parts of the assemblies.

4.4 Characterisation of the tested boards

All boards were visually inspected after the soldering trials, before and after the reliability tests. The visual inspection of the boards was carried out following the standard IPC-A-610D class 3.

4.4.1 Results before reliability testing

Before the reliability tests the following anomalies were found:

Board A

Some bridging, misaligned components, solder balling and solder residues were found in both types of solder and boards. Rework was carried out on most of the tin/lead and in all the lead-free assemblies. The following defects were present:

- One open joint in the tin/lead and lead-free boards;
- Two components placed with inversed polarity.

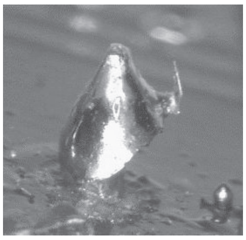

Figure 6 – Example of defect found: open joint.

Board D

Barrel fill was not complete on some leads of the heavier leaded components, although for most components, a good topside fillet was formed. The tin/lead boards showed less problems and only insufficient barrel fill and solder splash was found. The lead-free boards present more problems related to poor wetting, flux residues, defects like a blow-hole, solder spikes and blistering of a component were also found.

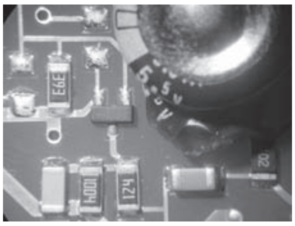

Figure 7 – Example of defect found: Blistering of the plastic coating.

4.4.2 Results after reliability testing

After the reliability testing the boards were submitted to functionality tests and visual inspection. The main issues reported are described in the following points:

Low temperature storage test

All the boards submitted to the low temperature storage test presented no visual change or damage. All the boards passed the functionality tests except the tin/lead versions of boards D and E. The origin of the faults was not identified. No solder joint damaged was visually evident.

High temperature storage test

No significant changes were noted in the boards, apart from some change in the appearance of the flux residue and slight discoloration.

- Board A: both tin/lead and lead-free failed the functional tests. No visually damage was found. Possibly component failure led to the fault.
- Board B: both solders failed in the electrical functional test due to one component distortion during the high temperature test.
- Board C: No visible changes found. All boards passed the functional tests.
- Board D: No other changes except some change in appearance of residues on board were found on the boards. Only the tin/lead board has failed the functional test due to component failure.
- Board E: One tin/lead board has failed the functional test, but no visible solder joint damage was located.
- Board F: No visible changes. All boards passed the functional tests.

Thermal cycling test

This test was very severe for all the boards. About 54% of the boards failed to function.

- Board A: Both solders failed the functional tests. Some joints showed signs of severe degradation but failure could be due to component failure. Some components are susceptible to failure when temperatures reach 100ºC.
- Board B: All boards passed the electrical tests at 3000 cycles except for one lead-free board that had a component failure. On the 6000 cycles only one tin/lead board survived, the remaining boards presented open joints and severe degradation.
- Board C: All boards passed the electrical tests. No significant changes apart from discoloration and joint degradation were observed.
- Board D: All boards have failed on the functionality tests. Cracks on the joints near the lead and the pad, damaged electrolytic capacitors (Fig. 8 a) and fillet tearing was observed (Fig. 8 b). The failures come from the two electrolytic capacitors, after replacing those components the boards became functional. There is a doubt if the failure is due to component or joint failure, because in most of the boards swelling and sometimes burst of these components was verified.
- Board E: Only two tin/lead boards have failed the electrical tests. These boards showed severe degradation of the tin/lead through-hole joints. Solder joint failure was likely to be the route cause of this result.
- Board F: All boards failed the electrical tests. The joints presented severe degradation and cracks near the leads.

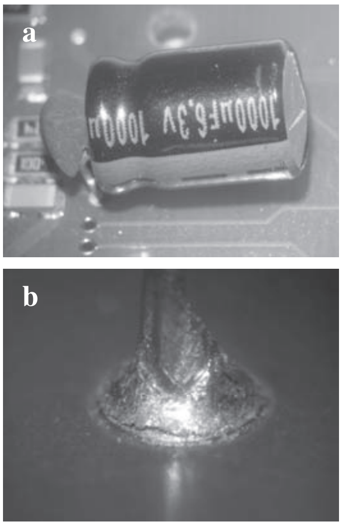

Figure 8 – Defects found on board D. a) Damaged electrolytic capacitor. b) Fillet tearing.

Thermal shock test

The thermal shock test showed no significant change in the visual inspection and only one lead-free component from board B has failed in the electrical functional test due to component internal damage.

Vibration test

No significant change in the visual inspection was found in all the boards and all have passed in the electrical functional test.

Component attachment strength test

All the boards showed good component strength, maintaining their initial values after testing (comparing with the non tested sample). The tin/lead boards that were submitted to the thermal cycling test have shown a decrease in the component strength. Lead-free ones presented equal performance comparing with the reserve boards and some showed slightly higher component strength after reliability testing.

4.5 Characterisation of solder joints by microscopy techniques

4.5.1 Optical microscopy

Board A

The tin/lead SMD's presented good joint appearance, the lead-free samples presented some voiding.

Board B

All the samples from board B showed good wettability. Both tin/lead and lead-free reserve samples (non-tested) showed good joints. The tin/lead samples did not have defects in any of them, the lead-free samples had voids in all the samples and cracks in the thermal cycling one.

Board C

In Board C the tin/lead reserve sample presented solder wicking (see arrow in Fig. 9). The solder wicking defect is characterised by the solder paste tending to wet the component termination rather than the pad and lead. This is due to the slow wetting of the pad and faster wetting of the termination, tin/lead terminations in lead-free alloys can produce this effect, because the tin/lead coating wets very fast and drags the solder up, can be caused by the profile or the soldering process. Pad solderability can be tested to compare different boards or process parameters. It can be seen that the solder is on both sides of the termination, nevertheless this joint is considered satisfactory. The tin/lead and lead-free samples did not have any degradation due to testing, except for the lead-free submitted to thermal cycling that had a small crack. All the lead-free samples had voids and cracks on the thermal cycled samples (see arrows in Fig. 10).

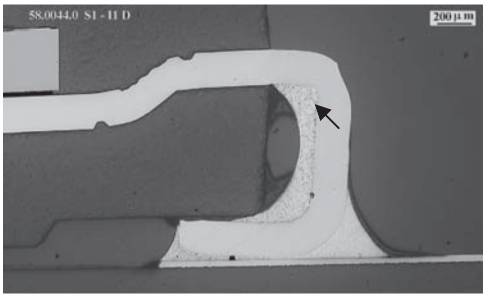

Figure 9 – Optical micrograph of sample board C: 62Sn/36Pb/2Ag; reserve (40X). Presents solder wicking (arrow).

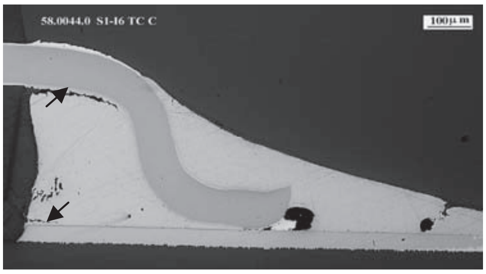

Figure 10 – Optical micrograph of sample board C: 96.5Sn/3.0Ag/0.5Cu; thermal cycling (3000 cycles; 0ºC to 100ºC) (100X). Crack propagation near the lead and pad (arrows).

Board D

These boards presented poor wetting, insufficient fill on the through-hole joints (less than 75% fill on the barrel), some cracks on the through-hole joints that suffered the thermal cycling test.

Board E

The tin/lead reserve sample presented good joints. In the lead-free solder joints some voiding is present. High temperature storage and thermal shock sample from both solders did not have any visible problems. For thermal cycling the tin/lead samples showed crack and the lead-free sample had little cracks. One of the tin/lead samples that was subjected to thermal cycling had an intergranular crack propagation near the interface between the solder and the lead (Fig. 11).

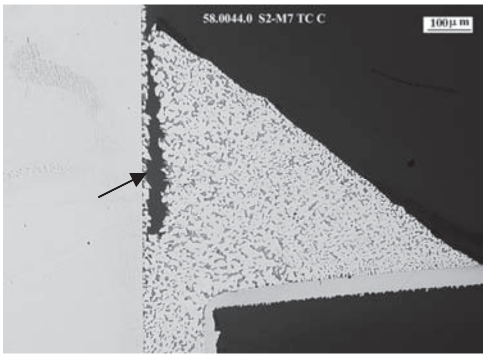

Figure 11 – Optical micrograph of sample from board E: 63Sn/37Pb; thermal cycling (3000 cycles; 0ºC to 100ºC) (100X). Intergranular crack propagation near the lead (arrow).

Board F

All through-hole components of the board F samples presented complete fill and good wettability. The lead-free through-hole joints submitted to the thermal cycling test presented cracks near the pad (Fig. 12 a); pad lifting appeared in almost every component (Fig. 12 b). The SMD joints showed good quality after testing and the tin-lead joints were in good conditions with only some voiding present.

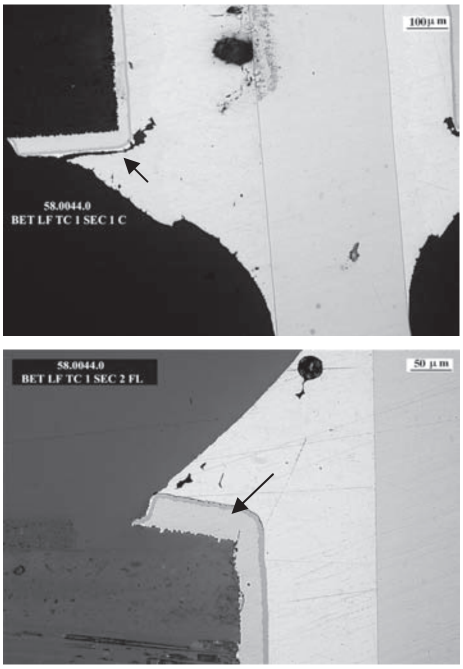

Figure 12 – Optical micrographs of samples from board F. a) 96Sn/3.0Ag/0.7Cu; thermal cycling (3000 cycles; 0ºC to 100ºC) (100X). Crack propagation near the pad (arrow). b) 96Sn/3.0Ag/0.7Cu; thermal cycling (3000 cycles; 0ºC to 100ºC) (200X). Pad lifting (arrow).

4.5.2 Scanning electron microscopy

Some samples were also analysed by scanning electron microscopy (SEM). Figure 13 shows, as an example, the reaction that takes place at the solder/pad interface. The micrograph was taken in a tin/lead joint of board F. It is observed that the entire intermetallic layer is composed of two sub-layers: the Cu_6Sn_5 near to the solder and the Cu_3Sn next to the copper substrate. It is normal to observe only the Cu_6Sn_5, because the overall layer development is not very extensive on service conditions.

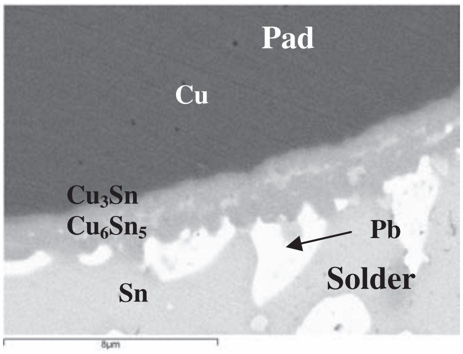

Figure 13 – Scanning electron micrograph of board F: 63Sn/37Pb microstructure near the copper pad.

The accumulation of (Pb) in front of the intermetallic interface is a consequence of the Sn-rich phase being consumed by the formation of the compound layer. The (Pb) does not participate in the formation of the Cu_6Sn_5 and Cu_3Sn intermetallics, this element simply accumulates at the interface between the Cu_6Sn_5 and the solder. The (Pb) element also has very low miscibility in (Sn), leading to two distinct phases in the microstructure.

On figure 14 the following evidences can be observed: Sn-matrix with (Ag) small particles, the (Ag) particles are not visible in the micrograph; (Pb) in large bright islands; copper in the matrix comes from the components and solidifies in front of the (Ni) barrier. (Ni) finish coating. No degradation of the microstructure is visible after the thermal cycling test.

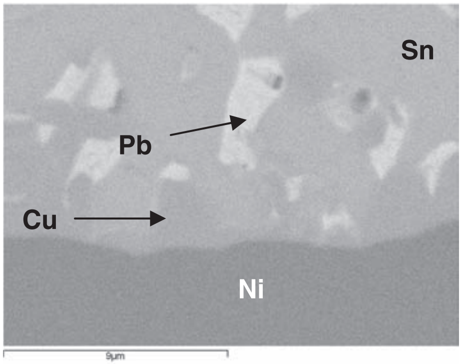

Figure 14 – Scanning electron micrograph of board F: 63Sn/37Pb; thermal cycling (3000 cycles; 0ºC to 100ºC). Microstructure near the lead.

Figure 15 shows an interface between solder and lead. (Cu) precipitates in front of the (Ni) barrier.

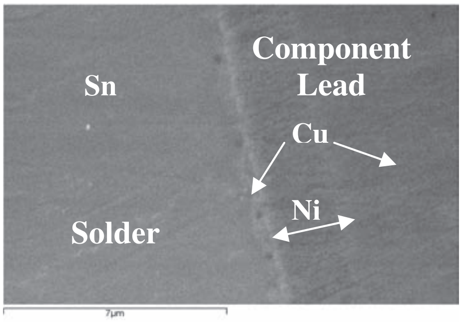

Figure 15 – Scanning electron micrograph of board F: Sn/Ag/Cu/Bi; thermal cycling (3000 cycles; 0ºC to 100ºC). Solder/lead interface.

The copper in front of the nickel barrier does not come from the pad, there is no dissolution from the pad. The copper comes from the solder or the lead of the components that are cut-off. On solidification the copper that has the same crystal structure as nickel, face-centered cubic (FCC), is the first to nucleate on such interface. On the board D the characterisation by SEM showed the nucleation of (Cu) on the pad in the form of Cu_6Sn_5 followed by the growth of large plates of Ag_3Sn (fig. 16).

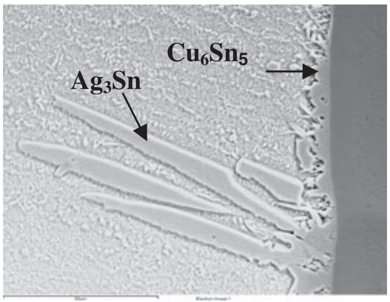

Figure 16 - Scanning electron micrograph of board D. a) Sn/Ag/Cu eutectic microstructure; b) intermetallics at the solder/pad interface.

In this characterisation it was also found a very well known defect: pad lifting.

Figure 17 shows a detail of pad lifting effect and the consequent crack on the board.

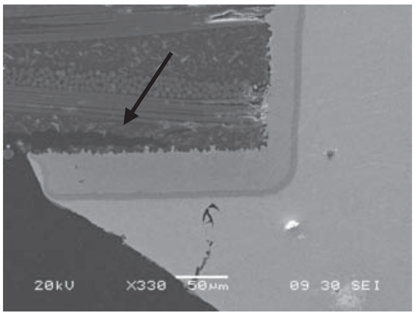

Figure 17 – Scanning electron micrograph of board F: Sn/Ag/Cu/Bi; Thermal cycling (3000 cycles; 0ºC to 100ºC). Evident pad lifting (arrow).

The pad lifting phenomenon is due to the mismatch between the coefficients of thermal expansion (CTE) of the components during the manufacturing. In table 9 it is shown the CTE's of the main constitutive elements of the board's components. In this case, the solder is mainly constituted by tin that has a higher CTE (23.5x10^{-6}/K) than the board (17x10^{-6}/K). The board expands during soldering, when the solder solidifies and the board cools down then the solder contracts more than the board, the pad edges contracts and can be lifted from the surface of the laminate.

Table 9 – Coefficients of Thermal Expansion of the different joint materials **[8, 13]**.

Material	CTE (x10^{-6}/K)
Sn	23.5
Ag	18.9
Cu	17
Ni	13
Pb	29
Cu_3Sn	18.4
Cu_6Sn_5	20
Laminate	17

4.6 Conclusions

In soldering trials carried out at the assembler's industrial facilities no major difficulties in the lead-free soldering process were reported. Especially reflow soldering process has been carried out with very few problems. Some soldering defects were experienced with the lead-free soldered products; namely bridging, solder balls, incomplete barrel filling. Blistering of some components in board D was also found. These defects and issues found during the soldering trials were standard problems, often seen in the lead processes. Most of them can be attributed to pre-heat and soldering temperatures in the process. The blistering found on some components of the board D is due to the incapability of some components to withstand the higher lead-free temperatures and/or to the presence of moisture and consequent poor storage of components.

After the reliability tests, most of the boards passed the electrical functionality tests, except for the thermal cycled ones. In general the lead-free joints showed good performance on the reliability tests carried out. The SMD (Surface Mount Devices) are less degraded than the through-hole joints for majority of the tests, this can be due to assembly process conditions and to expected performance of the through-hole joints under testing. The through-hole joints showed more defects than the other regular solders, like pad lifting, and crack propagation near the pads in almost all joints after the thermal cycling test. The board D samples that were submitted to thermal cycling have all failed the functionality tests. Although some cracks were found on the joints of the electrolytic capacitors it was not concluded that the faults come from these cracks, because these components do not stand the high temperatures imposed by the thermal cycle test. The lead-free through-hole joints of the board F samples showed poor performance, presenting more degradation on the lead-free joints, especially under the thermal cycling test. This can be related to the new lead-free wave solder alloy with corrosion inhibitors used by that company to replace the tin/lead alloy in the wave solder process.

From the reliability tests and after the characterisation can be concluded that the lead-free boards showed a good performance under testing, being equivalent or better than the tin/lead ones. The defects or anomalies found in most of the joints result from the manufacture process (voiding and pad lifting). For the through-hole joints the cracks that can be seen in some of the samples are always away from the interface and follow an intergranular fracture mode. The cracks did not propagate very far in the joint neither through the intermetallic layer, thus, indicating a good connection between materials, strong intermetallics, in both tin/lead and lead-free solders, and it should not compromise the integrity and functionality of the product.

5. General overview – environmental and economical impact

5.1 Environmental impact and main relevant factors of lead-free soldering

To producers and manufacturers, waste reduction, recovery and recycling should be and will inevitably be treated as a long-term goal with an ongoing effort. A product should be designed for minimal environmental impact with its full lifecycle in mind. Lifecycle assessment includes all the energy and resource inputs to a product, the associated wastes, and the resulting health and ecological burdens. The goal is to reduce environmental impacts from cradle to grave.

Lead is considered to be a cumulative poison; significant amounts can bring discomfort and disability. Some specific potential health problems include disorder of the nervous and reproductive systems, reduced production of haemoglobin, anaemia and hypertension. The main concerns related to the use of lead in the industry are:

- Landfill contamination;
- Effluent discharge from the production process;
- Worker's exposure through fume, dust inhalation and direct ingestion [11].

The environmental issues bring new concerns to the produces and manufactures that have to cope with these new changes. It is this side of the business that has to study and balance the alternatives in terms of cost and benefit.

Fumes emissions, leaching tests and occupational health

In terms of environmental studies several tests were carried out in some of the assembler's facilities. The objective was to investigate the environmental impact associated with the lead-free process and waste treatment in manufacturing, through the evaluation of pollution level involved by the use of lead-free solder during the assembly processes. Therefore, three main tests have been carried out in order to compare the results between the lead and lead-free solders:

- Sampling and analysis of fume emissions;
- Occupational exposure measurements;
- Leaching tests of soldered printed circuits and dross of the wave processes.

Samples from the reflow, wave and hand soldering processes, with different solder alloys, have been collected and analysed. In the environmental measurements carried out at the companies participating in the project it was observed that all emission results using lead-free solder pastes were lower than the obtained with lead containing alloys. For boards containing lead solders, the lead content values implies that should be considered as hazardous waste acceptable only at landfills for hazardous waste. For boards containing lead-free solders, the values were below the detection limits and can be considered as inert waste. In the occupational health measurements, these were under the limit values for organic compounds and metals in both types of solders.

5.2 Industrial guidelines for lead-free implementation

5.2.1 Economical study

In terms of economics the lead-free changeover brings big impacts to the assemblers and manufactures. The RoHS directive affects areas like: manufacturing, quality, design, purchasing, marketing, sales, finance and management. The first question that emerges from this directive is: what do I need to change/invest to cope with the new demands?

Each producer has to know their own process and some questions have to be answered:

- Is the present equipment is capable of lead-free manufacturing, in terms of temperature, process control, material)?
- Are the current facilities are capable? (separate manufacturing lines, stocks handling)
- Is new equipment is needed? (Soldering irons, wave soldering…)
- Is personnel training is needed? (purchasing, technical staff, engineers, designers)

Regarding equipment issues the wave process is the one that presents more difficulties due to the bath temperature increase, increased pre-heat temperatures, flux changes, longer wave contact time and high contents of tin in the solders. The following image shows the corrosion of a pot with lead-free solders where the assembler just removed the old bath and introduced the lead-free one on the same pot. The pots have to be prepared to the high contents of tin, new pots and coatings are available in the market and suitable for lead-free solders.

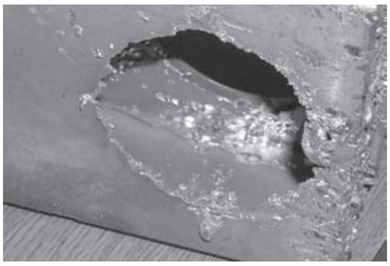

Figure 18 – Tin corrosion on a wave soldering machine pot [18].

The cost of producing is not a simple and straightforward issue. Many factors contribute for the overall cost:

- Solder product cost;
- Operational cost;
- PCB and component cost;
- Equipment cost;
- System cost.

The solder product cost includes metal elemental price, alloy compositional cost and production. Metal prices fluctuate with the market demand and the higher the content of an expensive metal in the alloy the higher the price of the solder. Production like ingots, powder, adding flux in the solder and others, bring indirect costs to the final price of the solder. The operational costs are different for reflow and wave. In reflow process using solder paste the main factors are:

- Electrical consumption for oven operation;
- Reflow oven maintenance;
- PCB change (if applicable);
- Component change (if applicable);
- Machine modification (if applicable);
- Nitrogen usage (if applicable);

In a wave soldering process:

- Solder replenishment required due to dross;
- Solder replenishment required due to compositional stability;
- Pot stability;
- Electrical consumption;
- PCB change (if applicable);
- Component change (if applicable);
- Machine modification (if applicable);
- Nitrogen usage (if applicable);
- Wave machine maintenance.

PCB and component cost are related mainly to the higher process temperature required. A change to a different PCB or component delivering a higher temperature tolerance may involve additional costs.

Regarding equipment most of the companies did not have any problems in adapting their reflow ovens to the lead-free processes, with a good profiling and optimisation the existing ovens can still be used. In the wave process the companies found more difficulties due to the higher process temperatures and two approaches were observed: some adapt their wave machines for lead-free (e.g. new pots and other parts), which represent a relatively low investment; and others calculated the estimated time for failure (corrosion in the pot, etc), ran the lead-free process in their old machines and bought a new wave machine at the end of the calculated lifetime.

The system costs involve the overall assessment of costs: solder material; process operational cost; component and PCB cost; equipment cost and amortisation; defects; product performance and reliability. The defects and reliability of the product are the most important factors of the system costs. A product failure is very expensive [19]. Most of the costs related with lead-free are coming from new equipments; energy consumption, due to higher temperatures and re-training the staff.

6. Final conclusions and future work

6.1 Final conclusions

This work presents a brief introduction to the area of soldering in electronics where a great evolution and effort in research and development of new solders and equipments can be seen. The lead-free “obligation” brought a new boost in this area, leading engineers to discover new solder alloys with the addition of elements, changing properties and characteristics, optimising processes.

From the practical part of this work it can be concluded that the SMEs were prepared for transition and are engaged in taking this opportunity to reach a higher level of performance. Some of the companies embraced this “forced” transition to upgrade and improve their process and facilities, bringing better capabilities and opportunities in their businesses. In the Economical chapter (5.2.1) some factors that should be taken into consideration when implementing the lead-free process are mentioned. It is natural that an SME prefers not to invest in new equipment but the companies present in this study showed that the purchase of new equipment that is suited and prepared to run lead-free brought less defects, easier transition, higher production levels; and on the other hand the companies that have chosen to adapt their process showed higher defect levels and more time consumed in tuning up the process. These factors also bring costs that sometimes are not visible, it should be the companies’ choice to calculate and decide whether or not to invest in new equipment. The main issue found in manufacturing and in reliability of the products is a component problem, an effort has to be made in order to fit the components in the lead-free processes and increase their availability on the market. Components should not only be RoHS compliant but they have to be able to withstand the temperatures imposed by the lead-free process.

The defects or anomalies found in most of the assemblers samples result from the manufacturing process (voiding and pad lifting). This shows the need for process optimisation (temperature profiles, fluxing, pre-heating…) in the manufacturing stage. The wave soldering is by far the most problematic process.

From the reliability tests it can be concluded that most of the faults found were due to component failures and not from the joint integrity. The degradation of both types of solders is similar, but the operators should be trained to identify the differences between the lead and lead-free solders. The inferior wettability and dull aspect of the lead-free alloys should be taken in account when doing visual inspection, non trained operators can be misled to classify those products as defective.

Comparing to the lead process the lead-free soldering process presented equal or better performance. The problems found in the new lead-free solders and processes it should not constitute a major problem in the reliability of the products. This shows that the lead-free soldering is ready to be implemented in the small to medium size enterprises, despite the issues that may be encountered on the way. These issues can be easily overcome with continuously process monitoring and tuning up. It is important to keep in mind that in order to reduce the cost of the soldering process and increase the reliability of the solder joints, companies should monitor or continue to monitor their processes and defects.

This work also allows to conclude that the partnership between universities, research and development centres and industry is a must for the evolution and improvement of the companies processes and products. A lot of work was done that brought great benefits to this sector.

6.2 Future Work

Following the trend of the electric and electronic industry and the ELFNET Roadmap [20], some recommendations for the future work should be approached:

- Thermally compatible components;
- Design for reliability – new tools and processes for high reliability products;

- High reliability solders – modifications of alloys (adding ternary elements, nano particles to improve properties);
- New materials to CTE matching – decrease the CTE's differences in a board;
- Improvement in the soldering and de-soldering processes including rework and repair – new heat management to mitigate collateral damage (laser soldering, low temperature soldering, vapour phase soldering, optimised selective soldering);
- Harmonised reliability standards and data for the lead-free soldering;
- New technologies for inspection and testing of components and joints;
- Use of refurbishment material for low cost reliable reusable components.

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