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QUALITY REQUIREMENTS IN LEAD-FREE SOLDERS IMPLEMENTATION IN ELECTRONICS

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ABSTRACT

After the RoHS and WEEE directives came into force on 1st July 2006, producers of certain categories of electrical and electronic equipment are not able to place on the market products that contain lead, mercury, hexavalent chromium, cadmium, polybrominated biphenyl flame retardants and polybrominated diphenyl ether flame retardants. Therefore, solders, as commonly used electronic materials, had to be redesigned into lead-free solder materials, which were widely investigated in the last decade.

The quality requirements for lead-free solders implementation in electronics, according to ISO 14040, are presented in this paper through the life cycle assessment analysis of these advanced ecological materials.

Key words: Lead-free solders, ISO 14040, life cycle assessment

1. INTRODUCTION

Lead (Pb) is a major constituent of solders used extensively within electrical and electronic equipment and there are environmental concerns over the amount ending up in land-fill. As a result attention has been increasingly focused on the potential of Pb-free soldering which can also provide improved reliability and mechanical strength.

First note to bring a sharp focusing of attention to this environmental problem was a publication given in 1998 as the second draft of a proposal for an EC Directive on WEEE - Waste from Electrical and Electronic Equipment [1]. Although principally about recycling, the draft contained clauses aimed at banning the use of Pb in certain categories of electrical and electronic equipment. There was also a proposal to ban halogenated flame retardants used in the manufacture of the bare circuit boards and equipment housings.

The drive to reduce the level of use of hazardous materials is not new of course [2]. For example, lead in domestic water pipes and plumbing solders, petrol, paint and fishing weights etc., has long been the centre of environmental pressures. Printed circuit boards (pcbs) prevade every form of electronic equipment and are therefore vitally important for a vast range of products. Any change in soldering technology to Pb-free materials, would therefore have major implications for the industry world-wide, involving many sectors including computers, telecommunications, and other electronics [3].

The Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC (commonly referred to as the Restriction of Hazardous Substances Directive or RoHS) was adopted in February 2003 by the European Union [4,5].

The RoHS directive took effect on 1 July 2006, and is required to be enforced and become law in each member state. This directive restricts the use of six hazardous materials in the manufacture of various types of electronic and electrical equipment - lead, mercury, hexavalent chromium, cadmium, polybrominated biphenyl flame retardants and polybrominated diphenyl ether flame retardants.

The Waste Electrical and Electronic Equipment Directive (WEEE Directive) is the European Community directive 2002/96/EC on waste electrical and electronic equipment (WEEE) which, together with the RoHS Directive 2002/95/EC, became European Law in February 2003, setting collection, recycling and recovery targets for all types of electrical goods and is part of a legislative initiative to solve the problem of huge amounts of toxic e-waste [1,6].

The directive imposes the responsibility for the disposal of electrical and electronic equipment waste 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 ecologically-friendly manner, either by ecological disposal or by reuse/refurbishment of the collected WEEE.

In addition to being able to conform to the RoHS and WEEE directives, another reason why the industry was in need of new solders was the increased demands on modern solder materials, e.g. the electronic components are becoming ever smaller, and the solders have to sustain higher temperatures and more severe temperature fluctuations; the surface to bulk ratio changes, which leads to different microstructural behavior; new technologies like the flip chip method require solder ball sizes of 50-100 μm and smaller [7].

Following the global trend and the proclaimed guidelines - for both electrical and electronic equipment - to administer waste materials and restrict the use of lead, the technologies for manufacturing reliable lead-free solder alloys was aggressively developing during last 10-15 years [3]. But, the possibility of a change to Pb-free soldering has highlighted a whole series of questions relating to awareness and dissemination of existing information, materials availability, soldering technology, implementation of any new technology, added costs, and competitiveness, as well.

2. ISO 14040 AND LIFE-CYCLE ASSESSMENT

ISO 14040 [8,9] describes the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements.

Life-cycle assessment (LCA) presents the approach, which allows for a comprehensive analysis of the environmental consequences of a product system over its entire life [10,11]. Such analysis is increasingly being used by industry, as a tool to investigate the influence of the product system on the environment and serves as a protection and prevention tool in ecological management.

LCA analysis contains four major steps as defined by the Society of Environmental Toxicology and Chemistry (SETAC) and more recently by the International Standards Organization (ISO) [12]:

1. *Goal Definition and Scoping* **-** lays out the rationalization for conducting the LCA and its general intent, as well as specifying the product systems and data categories to be studied.
2. *Life-Cycle Inventory (LCI*) - involves the quantification of raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents.
3. *Life-Cycle Impact Assessment (LCIA)* - characterizes the environmental burdens identified in the LCI and assesses their effects on human and ecological health, as well as other abiotic effects, such as smog formation and global warming.
4. *Improvement Assessment or Interpretation of Results* **-** uses findings from the analysis to identify and evaluate opportunities for reducing life-cycle environmental impacts of a product, process, or activity, or to reach conclusions and provide recommendations.

3. LCA ANALYSIS OF LEAD-FREE SOLDERS

The information presented by LCA analysis of lead-free solders summarizes the following [13]:

- Study's life-cycle assessment methodology;
- Environmental and health impacts of the solders evaluated;
- Limitations of the study and alternative data analyses;
- Steps circuit board manufacturers can take to reduce environmental and health impacts;
- Challenges to implementing lead-free soldering; and
- Information on cost and performance differences among the solder.

LCA evaluates the life-cycle environmental impacts from each of five major life-cycle stages: raw materials extraction/acquisition, materials processing, product manufacture, product use, and final disposition/end-of-life [13-16].

Table 1 describes each of these stages for a solder product system. The resource flows (e.g., material and energy inputs) and the emissions, waste, and product flows (e.g., outputs) within each life-cycle stage, as well as the interaction between each stage (e.g., transportation) are evaluated to determine the environmental impacts. The LCA combines raw materials extraction and materials processing into one "upstream" life-cycle stage in the presentation of results.

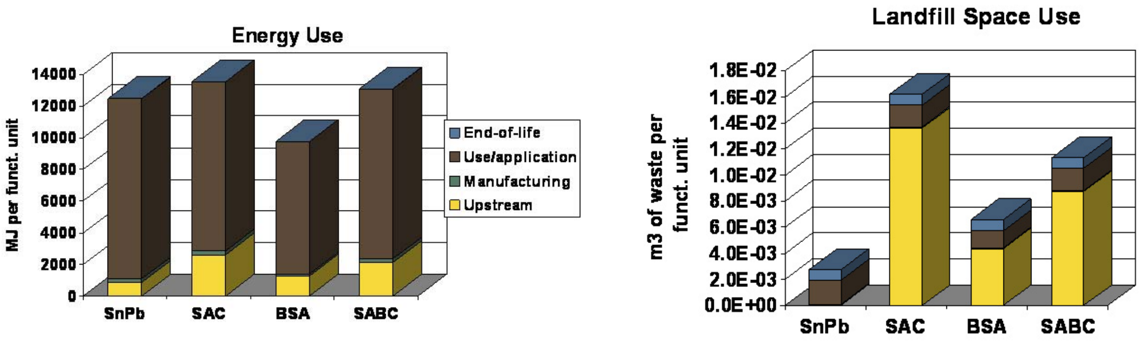
Eutectic tin-lead (SnPb) solder has long been the primary choice for assembling electronics due to its reflow properties, low melting point, and the relative ductility of the solder joints formed; however, concern over lead's relatively high toxicity to human health and the environment and ensuing international market and legislative pressures have led the electronics industry to begin switching to lead-free solders (Table 2, Fig.1). Although the performance of the metals and fluxes of many of the alternatives has been studied, their life-cycle environmental impacts have not yet been evaluated completely.

Table 1. Life-Cycle Stages for Solder Alternatives

INPUTS	LIFE-CYCLE STAGES	OUTPUTS
	RAW MATERIALS EXTRACTION/ACQUISITION (UPSTREAM) Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.	
Materials —►	MATERIALS PROCESSING (UPSTREAM) Processing natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.	—► Wastes
Energy —►	PRODUCT MANUFACTURE Processing materials into solder and solder alternatives.	
Resources—►	PRODUCT USE (USE/APPLICATION) Application of the solders onto printed wiring boards, which are then incorporated into various electronics products.	—► Products
	FINAL DISPOSITION (END-OF-LIFE) At the end of their useful lives, the solders, which are part of another product that is produced in the use stage, are retired. If reuse and recycle of the solder is feasible, the product can be transported to an appropriate facility and disassembled or demanufactured for materials recovery. Materials that are not recoverable are then transported to appropriate facilities and treated and/or disposed of.	

Table 2. Mostly used paste and bar lead-free solders compared to traditional Sn-Pb solder

Solder alloys	Makeup (%)	Density (g/cc)	MP (°C)	Application type
Tin/Lead (SnPb baseline)	63 Sn/37 Pb	8.4	183	Reflow and wave
Tin/Copper (SnCu)	99.2 Sn/0.8 Cu	7.3	227	Wave
Ti/Silver/Copper (SAC)	95.5 Sn/3.9 Ag/0.6 Cu	7.35	218	Reflow and wave
Bismuth/Tin/Silver (BSA)	57.0 Bi/42.0 Sn/1.0 Ag	8.56	138	Reflow
Tin/Silver/Bismuth/ Copper (SABC)	96.0 Sn/2.5 Ag/1.0 Bi/0.5 Cu	7.38	2115	Reflow



a) *b)*

b)

Figure 1. Selected impact category - specific Lead-free Solder results according to LCA: (a) energy use, and (b) landfill space use

The application of LCA analysis on investigated lead-based and lead-free solder alternatives, according to mentioned LCI and LCIA methodology, showed that among all of the solders SnPb has the highest impact category score for six impact categories; SAC has the highest impact category score in ten impact categories; SnPb has the lowest impact category score in five impact categories; and BSA has the lowest impact category score in seven impact categories.

More, if paste and bar solders are to be compared, the following is to be noticed [15,16]:

Paste solders

- Among all solders, SnPb has the highest impact category score for six impact categories; SAC has the highest impact category score in ten impact categories; SnPb has the lowest impact category score (shaded values) in five impact categories; and BSA has the lowest impact category score in seven impact categories.
- Among the lead-free solders, BSA has the lowest impact score in all categories except non-renewable resource use; SAC has the highest impact score in all categories except aquatic ecotoxicity and occupational cancer; and SABC has the highest impact score in occupational cancer and aquatic ecotoxicity, and the lowest impact score in non-renewable resource use.

Bar solders

- Among all of the solders, SnPb has the greatest impact category score in four impact categories, all of which are toxicity-related; SAC has the highest impact category score in the remaining twelve impact categories; SnPb has the lowest impact category score (shaded values) among the solders in five impact categories; and SnCu has the lowest scores in the remaining eleven categories.
- Among the lead-free solders, SAC has the highest impact score in all sixteen of the categories evaluated.

The following life-cycle stages drive the impact scores:

- For SnPb, eleven of the sixteen impact categories are driven by contributions from the use/application stage.
- SnCu has thirteen impact categories where the use/application stage is the major contributor.
- For SAC, the upstream life-cycle stage plays a more important role than it does for SnPb or SnCu. The upstream impacts are primarily from silver production. SAC has ten impact categories where the upstream stage is the main contributor. The use/application stage dominates four categories.
- The end-of-life stage drives the aquatic ecotoxicity impact category for all three solders.
- For all categories that are dominated by the use/application stage, except for occupational and public health categories, impacts result from the generation of electricity used in the wave application process.
- For the public and occupational health categories, inputs to the wave application process itself dominate the use/application stage.

There are several opportunities for reducing the overall environmental and human health impacts of solder used in electronics manufacturing based on the results of the LCA. Improvements in the upstream and use/application stages can be significant impacts resulting from these stages and their associated potential for improvement. Additional opportunities for improvement may exist in other areas of the solder life cycle.

4. CONCLUSION

As a contribution to a better knowledge of quality requirements in lead-free solders application in electronics, this paper presents the application of life-cycle analysis (LCA) in the frame of RoHS and WEEE directives and ISO 14040, as additional approach in investigation of solder alternatives, which among other influences include human health and environmental impact factors of lead-free solder alloys.

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