

NoNE lead-free soldering guideline

Version 2 – November 2004



SINTEF



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Preface

This Guideline is one of the deliverables from the project “Blyfri elektronikmontering hos SMF i Norden” (Lead free electronics assembly at Nordic SMEs) or “No Lead in Nordic Electronics” (NoNE), financed by the Nordic Industrial Fund (Projects 010134 and 02105, in the first and second phase, respectively) and coordinated by IVF. This is a synergy project between four Nordic national lead-free soldering projects.

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This Guideline is primarily intended as an orientation for companies planning to go lead-free. The target group is production managers and technicians. Results from the national Nordic projects have served as the primary input for the Guideline. For the second version, results from company cases have been included and the guideline has been updated. Future updates to the Guideline depend on national and Nordic financing. The latest version of the Guideline will be available at the project site: <http://www.ittf.no/none/>

Comments on the Guideline and suggestions for material to be included in future editions can be sent to Dag Andersson or Dag Ausen.

The authors would like to thank Kay Nimmo and Jeremy Pearce of Soldertec (<http://www.lead-free.org>) and Bob Willis (www.leadfreesoldering.com) for valuable input.

¹ B&O in Skive was sold to Flextronics during the project.

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1. Summary

Lead was one of the earliest heavy metals to be identified as a toxic environmental pollutant in widespread use throughout the world. Its use has been or is being phased out in many applications -- paints and leaded petrol, for example -- but the electrical and electronics (EE) sector has proved a stubborn case, in part because lead is still a key component of tin-lead solders used in equipment and components, notably printed circuit boards (PCBs).

The drive to exclude lead from EE products originated in Japan, where Sony found that advertising equipment as "lead-free" increased its market share. A new and powerful impulse was the introduction of EU directives for managing waste electrical and electronic equipment (WEEE) and restricting hazardous substances in product manufacture (RoHS).

A ban on the use of lead in electronics assembly in Europe was clearly inevitable. Naturally, the prospect generated worldwide interest in the development and implementation of lead-free solders. There are numerous lead-free solders available, some of which have been used in electronics production already. High-temperature solders have been used successfully in automotive applications, and some companies have blended these materials into their processes for consumer and military/aerospace applications. For most mainstream applications, tin/silver/copper (SnAgCu) appears to be the most popular replacement. This alloy has also been chosen to be the most popular benchmark, with SnPb (tin-lead) being the baseline, for testing any other lead-free alloys.

Given the higher melting points involved, there are implications for every stage of the lead-free PCB manufacturing, assembly and testing processes. There is also a new set of environmental issues, some of which are addressed by another Nordic Innovation Centre project, GreenPack (www.greenpack.org).

Many businesses anticipate difficulties in facing these challenges, and a number of them have joined forces through the NoNE project to coordinate their efforts to adjust to the ban.

1.1 The NoNE project

The first phase of the NoNE-project (full title: "Lead-free electronics assembly at Nordic SMEs") involved coordinating national projects running in Finland, Sweden, Norway and Denmark in 2001 – 2002. The second phase, focusing on the introduction of lead-free products, was completed by mid-2004. Nordic companies involved in the project include Bang & Olufsen (Denmark), Lövånger Elektronik AB and PartnerTech AB (Sweden), and Tomra Systems ASA, ABB Robotics AS, Nera Networks AS and Kitron Arendal AS (Norway).

This comprehensive NoNE "Guideline" for production managers and technicians at companies planning to go lead-free has been compiled and published in electronic format. Results from the national Nordic projects served as the primary input for the Guideline, which also includes a round-up of relevant national and international legislation, market developments, research projects, web links and detailed analyses of processes, materials and components. Some of the results from the different case studies carried out are also included in this updated guideline.

The results from the NoNE-project are open to all companies and organisations.

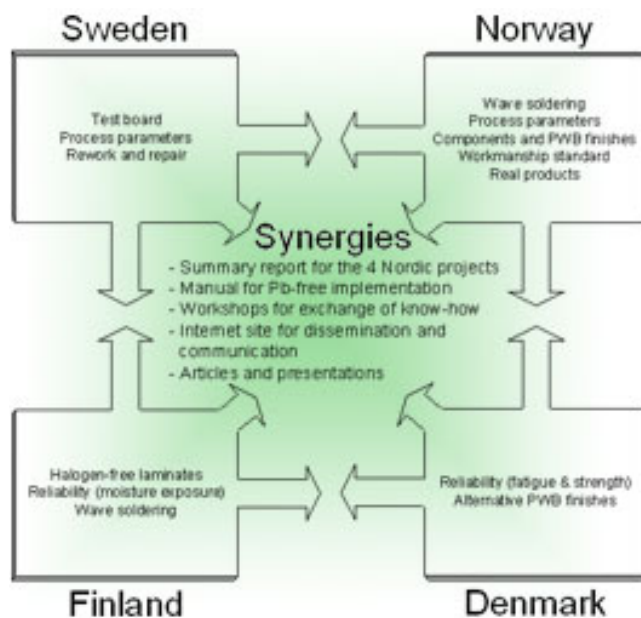


Figure 1.1 Nordic synergies in the NoNE- project

2. Introduction

For a brief introduction to the subject of lead-free soldering, leaflets in English, Norwegian, and Swedish have previously been produced within the project.*

All leaflets** can be downloaded at <http://www.ittf.no/prosjekter/none/site/information/>

Other publicly available material that complements this guideline includes the 1999 UK Government (DTI) reports co-authored by NPL – ITRI on lead-free soldering, and the 2000 update. These reports on lead-free soldering are downloadable from <http://www.npl.co.uk/ei/news/pbfree.html> and from <http://www.lead-free.org/download/index.html>

The European Lead-Free Technology Roadmap Version 2: February 2003, prepared by Soldertec, is downloadable from <http://www.lead-free.org/>

ZVEI (the German electrical and electronic manufacturers' association) have made two reports publicly available: "Lead-free soldering: Materials, Components, Processes" from 1999 can be downloaded in both English and German from <http://www.zvei.org/bleifrei/> (Click on "Leifaden Bleifreies löten"). The other report on production systems is as yet only available in German: "Stand der Anlagentechnik..." can be downloaded from the same site (click on "Anlagentechnik").

* They are based on a leaflet originally produced by Envirowise www.envirowise.gov.uk and can be downloaded from <http://www.lead-free.org>.

** A limited number of hardcopies of the leaflets are still available and can be ordered by contacting IVF (dag.andersson@ivf.se) or SINTEF (dag.ausen@ecy.sintef.no). Please specify language.

3. International legislation

3.1 General

In this chapter an overview of the legislation on restricting the use lead around the world is presented. Please note that this overview is not complete and that there are a lot of details not mentioned.

3.1.1 Convention on Long-range Transboundary Air Pollution

The United Nations Economic Commission for Europe (UN/ECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) came into force in 1983. It has been extended by eight specific protocols, one of which is the Protocol on Heavy Metals adopted in 1998.

It targets three particularly harmful metals: cadmium, lead and mercury. According to one of the basic obligations, parties will have to reduce their emissions for these three metals below their levels in 1990. The Protocol aims to cut emissions from industrial sources, combustion processes and waste incineration.

The Convention (CLRTAP): <http://www.unece.org/env/lrtap/welcome.html>

Protocol on Heavy Metals: http://www.unece.org/env/lrtap/hm_h1.htm

UN/ECE: <http://www.unece.org>

3.1.2 OSPAR convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR Convention") entered into force in 1998.

The objective is to prevent pollution of the maritime area by continuously reducing discharges, emissions, and losses of hazardous substances, with the ultimate aim of achieving concentrations in the marine environment near background values for naturally occurring substances and close to zero for man-made synthetic substances.

The OSPAR List of Chemicals for Priority Action contains lead and organic lead compounds.

The OSPAR Commission: <http://www.ospar.org/eng/html/welcome.html>

3.2 USA

The U.S. Environmental Protection Agency (EPA) has rated lead to be one of the top 17 chemicals to impose the greatest threat to human health.

The U.S. EPA has introduced a Toxics Release Inventory (TRI) rule, which aims at making information available to the public about lead emissions in their communities. The TRI lead rule lowers the reporting thresholds for lead and lead compounds to 100 pounds (approx. 45 Kilogram)

for facilities that manufacture, process, or otherwise use lead or lead compounds.

<http://www.epa.gov/tri/>

In USA there are also rules and standards for lead-based paint and lead dust cleanup levels. Read a summary of regulations at <http://www.epa.gov/opptintr/lead/regulation.htm>

In the different States there are different lead poisoning prevention statutes regulating lead in for example paint, batteries, and packaging. Read more at

<http://www.ncsl.org/programs/ESNR/pblaw99.htm>

Although a number of states are heading towards lead-free and/or recycling regulation there is not yet a published federal position. However, the EPA continues to put pressure on lead users.

3.2.1 California Legislation

In September 2003 Governor Gray Davies signed Senate Bill 20 concerned with take-back, recycling and design of various types of electronics equipment. A \$6-\$10 levy on PC's and TV's will pay for recycling. Campaigners have already criticised manufacturers for weakening the measure.

There is a statement on lead and other hazardous materials, with a link to the EU RoHS Directive. However, whether or not this applies to goods other than "devices with video displays greater than 4 inches", will not be clear until the Department of Toxic Substances Control drafts regulations to implement the law.

Recent California bill (SB 20, Sher. Solid waste: hazardous electronic waste)

"...shall adopt regulations... that prohibit an electronic device from being sold... in this state if the electronic device is prohibited... in the European Union... to the extent that Directive 2002/95/EC... prohibits that sale due to the presence of certain heavy metals..."

The law will be applied from January 2007. It is still unclear which product categories the law covers. This is to be resolved when text of legislation is developed.

Various other states in the US are also considering e-waste legislation.

3.3 Japan

In Japan the Home Appliances Recycling Law came into force in April 2001. Its initial target is to promote the recycling of TV sets, refrigerators, washing machines, and air-conditioners. Although this law doesn't mention the use of leaded products, there is another law forbidding companies from putting any kind of waste leaching toxic elements into the environment.

Japanese electronics manufacturers have come the farthest with lead-free products. They have acted on the coming EU directive.

Japan Electronics and Information Technology Industries Association (JEITA) is one important organisation in Japan that actively promotes environmental preservation measures. It also makes

proposals on industry policies, supports technological development, and promotes the diffusion of products in new fields.

See: <http://www.jeita.or.jp/english/index.htm>

3.4 China

In China, a RoHS-like law has been introduced by the Ministry of Information Industry (MII): “Management Methods for Pollution Prevention and Control in the Production of Electronic Information Products”

- Leading feasibility study of applying RoHS in China
- Rulemaking agenda includes preparation of regulations and technical standards
- Addresses chemical substance use, recycling, and take-back

Initial plans to phase-in requirements July 2003 to July 2006

- July 2003 certify plans to reduce toxic and harmful substances
- July 2006 ban on specified substances

The law will include manufacturing and imports. No specific date for publication has been set.

Electronic information products covered;

- communications equipment
- computers and peripherals
- electronic instruments
- electronic meters
- electronic parts and components
- household electrical appliances
- radar and related products
- radio and TV broadcasting equipment
- special electronic equipment
- special materials for electronic products
- other [electronic information products]

The chemical substances covered;

- As included in RoHS
- Pb, Hg, Cd, hexavalent Cr, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE)

3.5 EU

3.5.1 RoHS directive

RoHS, Restriction of the use of certain Hazardous Substances in electrical and electronic equipment.

Consumer and IT products are the categories mainly affected. The Directive requires the use of lead, mercury, cadmium, hexavalent chromium and two types of brominated flame retardants, PBB and PBDE to be phased out from products put on the market after 1st July 2006. Some exemptions have been given for the continued use of lead and other hazardous materials in essential applications. One such example is high lead alloys used for high temperature soldering. This type of tin-lead solder generally contains 90 or 95% lead and is used for internal component connections and for other similar requirements. Slightly extended target dates also apply to high reliability products such as network infrastructure.

Categories of electrical and electronic equipment covered in RoHS are eight out of 10 categories defined in the WEEE (Waste from Electrical and Electronic Equipment) directive.

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment
4. Consumer equipment
5. Lighting equipment
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7. Toys, leisure and sports equipment
10. Automatic dispensers

Some of the exemptions:

- Lead in glass of cathode ray tubes, electronic components and fluorescent tubes.
- Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead),
- Lead in solders for servers, storage and storage array systems (exemption granted until 2010),

- Lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication,
- Lead in electronic ceramic parts (e.g. piezoelectronic devices).

The definition of maximum concentration values in the RoHS-directive has been heavily discussed. At the moment, a draft commission proposal exists stating:

For the purposes of Article 5(1)(a) in the directive: a maximum concentration value of 0.1% by weight in homogeneous materials for lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) and of 0.01% weight in homogeneous materials for cadmium shall be tolerated. Homogeneous material means a material that can not be mechanically disjointed into different materials.

The RoHS directive:

http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=32002L0095&model=guichett

Draft commission decision on maximum concentration values:

http://www.tintechnology.biz/soldertec/soldertec.aspx?page_id=2841&SelectedMenu_ID=-1

3.5.2 WEEE-directive

Main requirements of the WEEE Directive

Member States to set up systems to encourage separate collection of WEEE; and are to set up systems which will allow the return of WEEE free of charge to the final holder;

No mandatory requirement for householders to separate all WEEE. Member States must instead seek to minimise co-disposal and encourage appropriate behaviour;

Retailers are to ensure that WEEE is taken back on a one to one basis when a new, equivalent type, product is supplied; but Member States can provide that retailers make alternative arrangements instead, provided that they are free of charge to the final holder of the WEEE.

By 31 December 2006, Member States must achieve a collection rate of at least 4 kilograms on average per inhabitant per year of waste electrical and electronic equipment from private households;

Member States to ensure that all WEEE collected from private households is transported to treatment facilities authorised under Article 6. Article 6 sets down standards which treatment facilities will have to meet;

Member States are to ensure that systems are set up by producers to provide for recovery and re-use of separately collected WEEE according to set recovery, re-use and recycling targets. Targets are set as a proportion of collected WEEE from private households;

The WEEE-directive:

http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexapi!prod!CELEXnumdoc&lg=EN&numdoc=32002L0096&model=guichett

3.5.3 The EU Directive on End-of-Life Vehicles

Objectives: “This Directive lays down measures which aim, as a first priority, at the prevention of waste from vehicles and, in addition, at the reuse, recycling and other forms of recovery of end-of life vehicles and their components so as to reduce the disposal of waste, as well as at the improvement in the environmental performance of all of the economic operators involved in the life cycle of vehicles and especially the operators directly involved in the treatment of end-of life vehicles.”

The directive covers vehicles and end-of-life vehicles, including their components and materials. It means that vehicles put on the market after 1 July 2003 shall not contain lead, mercury, cadmium or hexavalent chromium.

In Annex II exemptions are listed. One of the exemptions is lead in solder for electronics. Solders and components that continue to contain lead must however be identified through specific labelling. They must also be dismantled and treated according to relevant regulations if the total lead content in electronics amounts to 60g Pb per vehicle or more.

In Annex II a limit for lead is also specified; maximum concentration up to 0.1wt% per homogeneous material, if not intentionally introduced.

The directive also sets targets for collection, treatment, control of disassembly and use of secondary materials.

The directive: http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_269/l_26920001021en00340042.pdf

Annex II: http://europa.eu.int/eur-lex/pri/en/oj/dat/2002/l_170/l_17020020629en00810084.pdf

3.5.4 Denmark

Denmark was the first country in the world to have restrictions on cadmium, mercury, nickel, and lead for some products.

It is not sufficient to target individual products when forbidding lead use, because it is found in so many products. Products affected by the ban are to include those containing lead compounds, such as plastic stabilisers, as well as metallic lead.

The ban came into force March 1, 2001 for many products and comprises import and marketing of products containing lead but not products produced in Denmark exclusively for export. Other products will not be affected for some years, due to the fact that alternatives still are undergoing trials or are at the development stage.

Electronic components are allowed until further notice. <http://www.mst.dk/>

3.5.5 Sweden

Lead is mentioned in several regulations in Sweden, e.g. for paint, batteries, and petrol.

The Government presented the fifteen environmental objectives in 1998 (Swedish Environmental Quality Objectives). In February 2001 the Swedish government presented a Bill “A Chemicals Policy for a Non-toxic Environment”. The Bill clarifies one of the environmental objectives “A Non-toxic environment”, setting out five specific targets and strategies on how to achieve them. One of the five targets is that new products will be as free as possible from lead by 2010 at the latest.

The implementation of RoHS and WEEE-directive in the Swedish law is expected to be completed during the spring 2005.

The WEEE directive is proposed to be implemented largely by replacing the present law on producer responsibility (2000:208). Responsible is the Ministry of the Environment (www.sweden.gov.se)

The Swedish Chemical Inspectorate (www.kemi.se) is responsible for the implementation of the RoHS directive.

Beyond what is stated in the RoHS directive, on May 6 2004, the Swedish Chemical Inspectorate was commissioned by the Swedish government to investigate the implications of a national ban on the flame retardant dekaBDE.

3.5.6 Norway

The implementation of RoHS and WEEE-directive in the Norwegian law is done during the autumn 2004. The RoHS regulations will be found in “Produktforskriften”. SFT, the Norwegian Pulltion Agency responsible for the implementation, have gathered relevant information at their web:

<http://www.sft.no/ee/index.html>

Lead is mentioned in several other regulations in Norway about e.g. petrol, sewage sludge, and batteries. Norwegian environmental authorities have adopted an objective to reduce the emissions considerably for lead no later than 2010. Lead is present on the list of prioritised substances as well as on the observation list. The observation list is a list of substances for which companies should exercise caution.

Norway's action plan for hazardous substances:

<http://odin.dep.no/md/engelsk/publ/rapporter/022051-220005/index-dok000-b-n-a.html>

Information on the observation list (in English)

<http://www.environment.no/Topics/Chemicals/obs/obs.stm>

The observation list (in Norwegian)

<http://www.mistin.dep.no/Tema/Kjemikalier/prioritetslisten/prioritetslisten.stm>

3.5.7 Recommended Guidelines

In UK, Envirowise (www.envirowise.gov.uk) has published a guide which explains the impact of the forthcoming WEEE and ROHS Directives and provides an overview for managing directors on the business actions they need to take. The guide details the types of companies affected, the financial obligations that the legislation will impose and the cost savings that companies can achieve by acting now. It also emphasises that companies who ignore the advice risk incurring excessive and unnecessary costs. A second guide, GG416, is designed to help marketing, design and operations executives understand the legislation and the actions that a business needs to take. The guidelines gives a good introduction to the actions needed, and could be downloaded at:

Business actions:

<http://www.envirowise.gov.uk/envirowisev3.nsf/key/GG415>

Marketing, design and other operations:

<http://www.envirowise.gov.uk/envirowisev3.nsf/key/GG416>

4. Market demands

As mentioned earlier, at the moment market pressure is the most important driving force towards lead-free products. This is particularly true for consumer electronics, where Japanese producers have set ambitious goals for the phase-out of lead in electronics.

So, where does the world stand on lead-free products? In Europe there has been a sustained pressure for legislation over the past 4-5 years. “Everyone” is waiting for the RoHS-directive to come into force. The strong opposition against the directive illustrates the non-proactive attitude of many European companies to this kind of regulations. The European lead-free technology roadmap 2001 from SOLDERTEC (see <http://www.lead-free.org/>) is a good reference for the situation in Europe. The roadmap was updated in 2003. Based on survey data across leading European companies, this second roadmap examines the current status of technology implementation in Europe. It covers areas of key interest such as which alloys are being used, what research and business issues remain and what timescales are projected for the technology to be in place by sector. The roadmap is essential reading to benchmark your company as July 2006 approaches.

In North America, there is some increase in activity underway to qualify lead-free materials and processes primarily driven by global electronics market competition.

In Asia, the situation is almost the opposite of that of North America. In Japan the entire electronics assembly industry is aggressively pursuing lead-free electronic products. More than 90% of the domestic electronics is expected to be lead-free by the end of 2003. Figure 4.1 below shows the goals for some of the leading Japanese companies towards lead-free electronics.

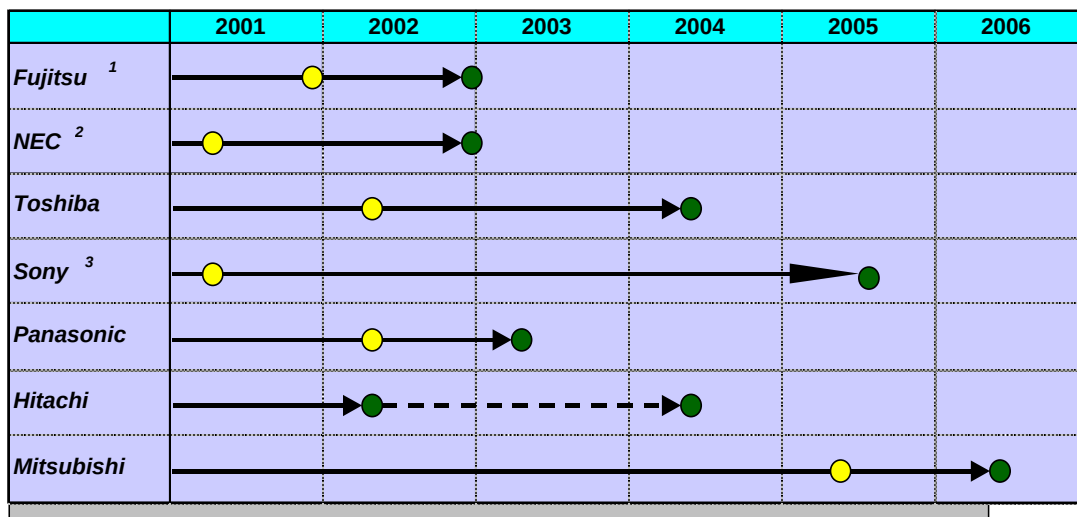


Figure 4.1 Strategy for elimination of lead from electronic products from some Japanese companies.

Some examples of lead-free products are shown below in Figures 4.2, 4.3 and 4.4.



Figure 4.2 SONY Mini-Disc Walkman



Figure 4.3 SONY Color TV "WEGA" series.

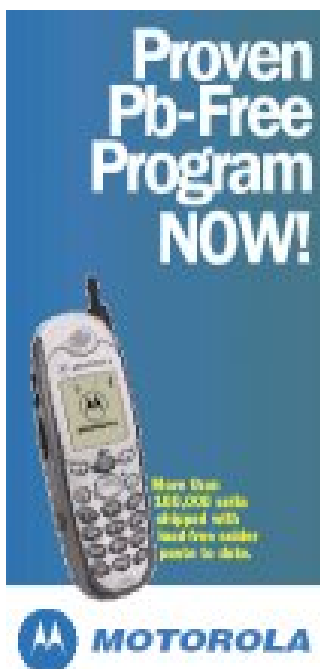


Figure 4.4 Motorola mobile phone (December 2001)

5. International research projects

5.1 ELFNET

ELFNET (European Lead Free soldering NETwork) is a European research network of the national organisations, technical experts and industry bodies in electronics.

ELFNET provides a platform to coordinate, integrate and optimise research, enabling electronics producers in the EU to meet an EU directive to introduce lead-free soldering by 1 July 2006.

ELFNET is supported by the European Commission and operates in 19 European countries. By facilitating ‘best practice’, ELFNET will continue to contribute to Europe’s competitiveness in electronics manufacturing beyond 2006.

ELFNET working activities are organised in a structure optimising the efficiency of the network for a collective advantage.

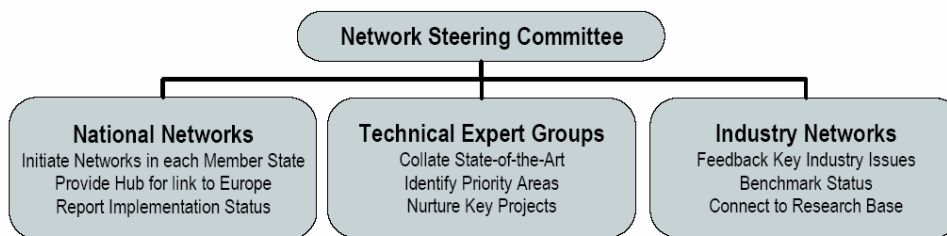


Figure 5.1 ELFNET structure.

The project is free to join for other companies and organisation than the 35 Founder members. ELFNET invites applications for membership via its website www.europeanleadfree.net. It's recommended to join the project as Affiliate member or Subscriber. More details could be found at the web.



Project web: <http://www.europeanleadfree.net>

5.2 GreenRose

This is a major technology transfer project based on a new organisational model whereby European electronics trade association's contract leading research organisations to carry out work to benefit their members. In this case, the project will collate, develop and deliver technologies relevant to removal of hazardous substances from electronics and deliver to the European SME community. A range of methodologies will be used including case studies, pilot lines and training packages. The project will consider halogens, cadmium, hexavalent chromium and mercury substances as well as lead-free soldering.

The main objective of the GreenRoSE project is to provide European SMEs of the electronics sector with the knowledge & tools to produce hazardous substances-free (in particular lead-free soldered and halogen free) electronic equipment with defined quality and reliability. This environmentally sound electronic production is the new environmental and business challenge as reflected in European legislation – RoHS, WEEE (Directive on Waste Electrical and Electronic Equipment), EuE (Directive on establishing a framework for Eco-design of End Use Equipment) – and in a worldwide trend towards “Green Electronics”.

The project period is January 2004 – December 2006. The project is funded under EC FP6 as a collective research project. Project coordinator is Abelia, Norway.

5.3 LFS for SME's

This European collaborative project brings together leading European Research Organisations and a group of SME's to study aspects of lead-free soldering that are particularly relevant to SME's and to create and deliver guidelines and training packages. It is the only current major collaborative project to study issues related to hand soldering, vapour phase soldering and laser soldering.

The project period is September 2003 – September 2006. The project is funded under EC FP5 as a CRAFT project. Project coordinator is Axtron, The Netherlands. Project web-site:

http://ica.cordis.lu/search/index.cfm?fuseaction=proj.simpdocument&PJ_RCN=6397921&CFID=1102052&CFTOKEN=88271845

5.4 Other projects

Since the beginning of the 1990s, prompted by environmental concern and in anticipation of upcoming legislation, research projects have been conducted both in Europe, USA, and Japan. An overview of the projects up to 1999 is found in the NPL – ITRI 1999 report on lead-free soldering and the 2000 update. These reports on lead-free soldering are downloadable from

<http://www.npl.co.uk/ei/news/pbfree.html>.

According to the 1999 report the main conclusions that could be drawn from research projects performed up to that point were:

- The wetting achieved when using lead-free solder alloys with “modified reflow cycles is acceptable.
- Most lead-free alloys are compatible with existing paste and foam/spray flux systems.
- Lead-free alloys are compatible with many lead-free board finishes.
- The reliability of the joints produced using lead-free soldering technology proved to be good
- Many of the research programmes have determined that tin-silver-copper alloys proved to be the most promising solder for general use.

According to the 2002 Soldertec roadmap (see <http://www.lead-free.org/>) the greatest need for further research is identified in the following areas:

- High temperature (=high lead containing) solder replacement
- Component temperature resistance
- Reflow equipment modification
- Rework

ELFNET is building a database on projects that can be accessed from the project web:
www.europeanleadfree.net

Information on most ongoing projects will be found here.

6. Materials and components

There are numerous lead-free solders available today, some of which have been used in electronics production already. High-temperature solders have been used successfully in automotive applications, and some companies blended these materials into their processes for consumer and military/aerospace applications.

6.1 Preferred solder alloys

SnAgCu

This alloy composition appears to be the most popular replacement. This alloy has also been chosen to be the most popular benchmark, with SnPb being the baseline, for testing any other alloys. The Solderotec recommendation from 1999 is found at http://www.lead-free.org/download/files/pdf/lead_free_thewayforward.pdf

There are many different variations from this alloy. Generally tested alloys have been Sn + [3,0-4,5] % Ag + [0,5 - 1,5] % Cu. The most popular seems to be Sn/3,8Ag/0,7Cu. There are two recommendations one by NEMI (Sn/3,9Ag/0,6Cu) and one by JEITA (Sn/3,0Ag/0,5Cu). The JEITA recommendation might be more interesting because there are some indications that the Japanese electronics companies will start to use it.

Concerns with this alloy family include higher processing temperatures (216 - 217°C) and the leaching of Ag from the solder into landfills. It should also be noted that metals cost for this alloy is about 2.5 times that of SnPb eutectic.

SnCu

This alloy composition is a low cost alternative for wave soldering. It's main area of use and is compatible with most lead bearing finishes. Process considerations must be addressed with this alloy, which has a higher melting temperature (227°C) than most SnAgCu alloys. Metals cost for this alloy is about 1.5 times that of SnPb eutectic.

SnAgBi

This alloy has been chosen as a candidate alloy, especially for use in SMT applications. The major concerns of Bi are fillet lifting that occurs in SnPb through hole applications, embrittlement, its toxicity, and low melting phase. There are also concerns with their lack of compatibility with lead bearing finishes, the leaching of Ag into landfills, and difficulties with reclaiming other metals during recycling due to Bi. Metals cost for this alloy is about 2.5 times that of SnPb eutectic.

SnZn

Although this alloy has lower melting temperature (<200°C), there are concerns with the oxidation of Zn and the long-term corrosion of the finishes soldering joint. This alloy also requires special fluxes, and its wetting characteristics are not as good as SnAgCu.

SnAg

This alloy has a slightly higher melting point (221°C) than SnAgCu, and is comparably in price to this alloy. Because it has been used for years in step soldering and special applications (i.e., die attach), there is an extensive database, which is attractive to companies looking for backup data, but there are concerns with the leaching of Ag from the solder into landfills.

According to the Soldertec European Lead-Free Technology Roadmap Ver 1: February 2002 (responses from 48 organisations, see <http://www.lead-free.org/>) the preferred alloys for soldering are as illustrated in Figures 6.1, 6.2 and 6.3 below.

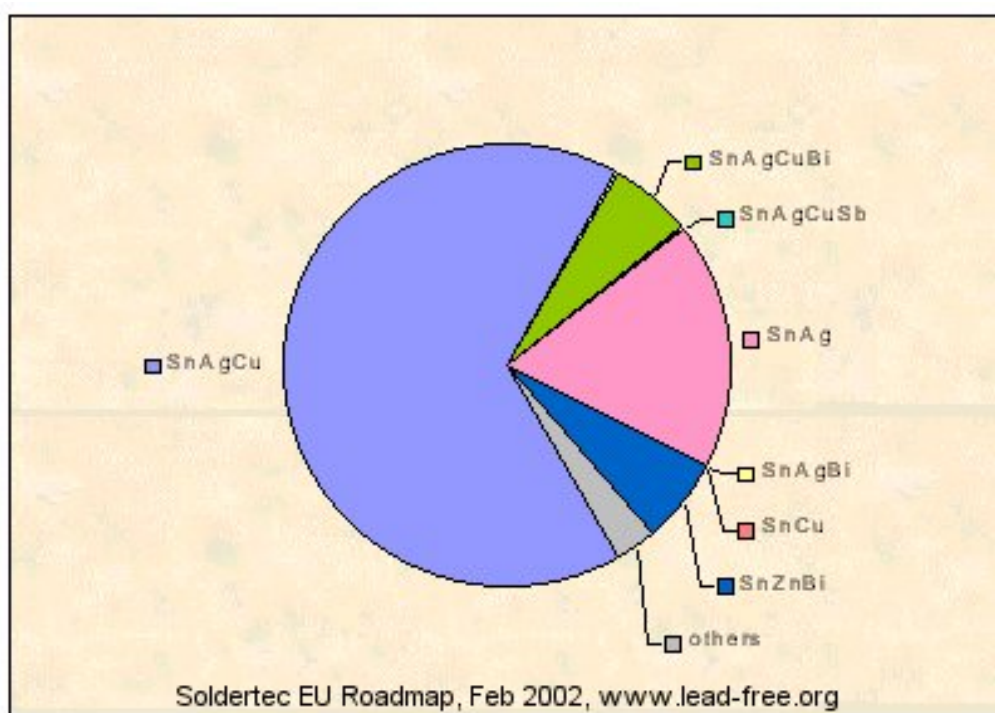


Figure 6.1 Alloys for reflow soldering

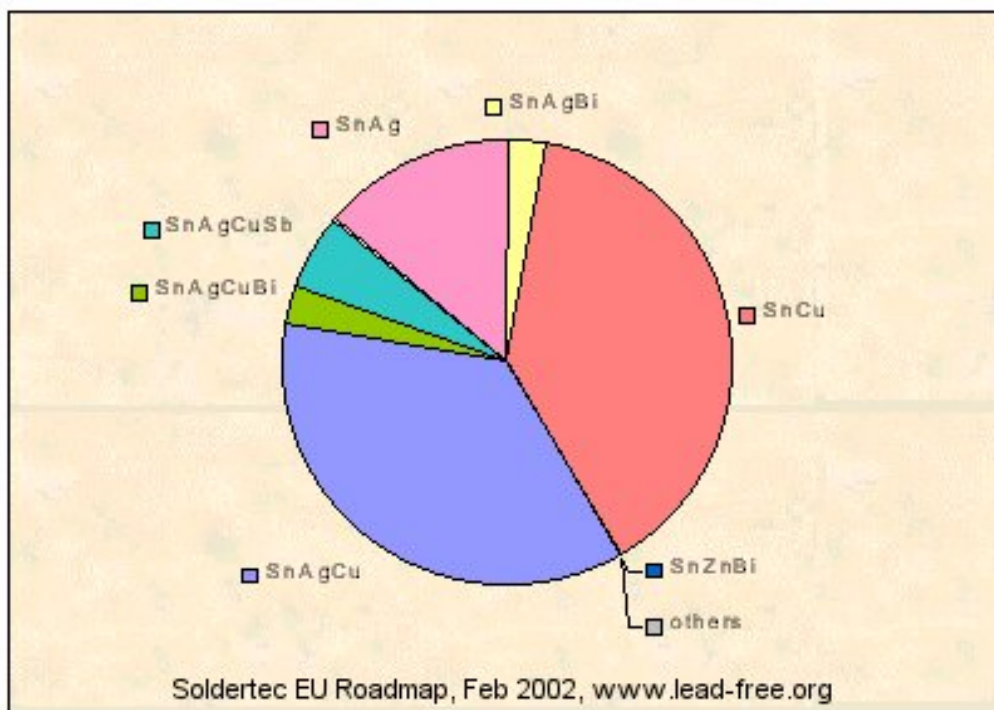


Figure 6.2 Alloys for wave soldering

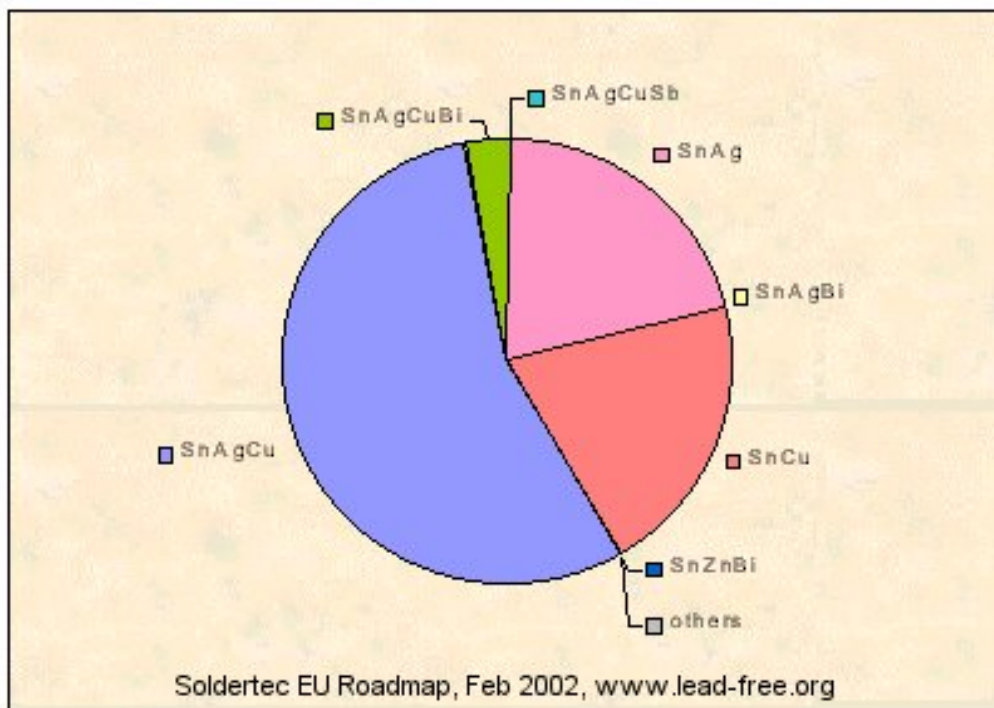


Figure 6.3 Alloys for hand soldering

6.2 Solder pastes

SPM in Denmark has carried out a project evaluating 12 different types of SAC² type solder pastes by comparative testing. The project called “2nd generation lead-free solder pastes” (SPM-170), has been carried out by Bang & Olufsen and Delta in cooperation.

A large number of suppliers of lead-free solder pastes have been studied as shown in table 6.1.

Table 6.1 List of solder pastes and local (DK) suppliers evaluated in the Danish SPM-project.

Manufacturer	Supplier	Material	Received date	Test run
Almit:	Venso Elektronik AB, Roland Olsson, Tel.+46 313400250	LFM 48 X TM-HP	29-01-2004	29-01-2004
Alpha-fry:	Teleinstrument, Finn Ryan, Tel. 76251818	OM-310	10-12-2003	29-01-2004
Cobar:	PC-Trading, Ingward te-Pas, Tel. 86741233	S9M-XM3S	10-12-2003	29-01-2004
Elsold / Amtech:	Boliden, Jesper Kafton, Tel. 43268300	SM-388	10-12-2003	22-01-2004
Indium Corporation:	Ketec, Keld Kortsen, Tel. 70267700	NC-SMQ 230	04-02-2004	17-02-2004
Interflux:	Interflux DK, Leif Fenger, Tel. 75383922	IF9009lt	28-11-2003	29-01-2004
Kester:	Inimar K/F, Lars Bøndergaard, Tel. 45936262	R905	12-12-2003	29-01-2004
Koki:	KOKI, Hans Chr Iversen Tel. 43 71 40 60	S3X58-M405	26-12-2003	22-01-2004
Multicore:	CYNCRONA, Torben Bo Nielsen, Tel. 87426675 (B&O)	CR39	on stock	17-02-2004
Multicore:	CYNCRONA, Torben Bo Nielsen, Tel. 87426675 (B&O)	LF300	on stock	17-02-2004
Senju:	HIN, Martin Fredslund, Tel. 76259090	M705-GNR360-K	26-11-2003	29-01-2004
Tamura	Tamura Kaken UK, Hideki Kubota, Tel. +44 1604768888	TLF-204-93	06-01-2004	29-01-2004

Many parameters have been studied:

- Particle size
- Slump and hot slump
- Printability
- Reflow properties
 - o Wetting properties
 - o Solder spread and flux residues
- Surface insulation resistance (SIR)

A single sided FR4 glass epoxy test board was supplied in two different board finishes:

- OSP
- Immersion gold

The paste product properties have been evaluated by SEM examinations, slump, hot-slump, printability, reflow and SIR testing.

² SAC – SnAgCu type lead-free solder

In general, the results show a relatively big difference in the hot-slump performance, as only 2 solder paste products exhibit perfect performance. 5 solder pastes are found to have acceptable performance, however, the remaining products and in addition the reference tin-lead pastes are found to suffer from serious slump bridging and paste lay down flow-out.

By printing and reflowing on OSP all of the tested pastes are found to have a wetting ratio of approx. 1.0, showing that the pastes only wet where printed. In contrast to this the wetting ratio on immersion gold, is found to vary from 1.1 to 1.7, showing a relatively good wetting ability of some pastes and major difference between the solder pastes tested.

The ability to recover from overprinting is found to be perfect for all of the pastes tested and similar to what is seen for the reference tin-lead paste. Solder ball formation on non-wetting epoxy laminate is also found to be perfect for all of the pastes, indicating a consistent paste reflow without solder splash/balling.

SIR testing confirmed perfect insulation resistance $>10 \times 10^4 \text{ M}\Omega$ for 5 of the tested pastes, and 7 pastes are found to have acceptable insulation resistance according to the IPC-TM-650 specification in the range of $1 \times 10^2 - 1 \times 10^4 \text{ M}\Omega$.

A summary of the main conclusions from the survey:

- Hot slump testing
 - o 2 solder pastes show perfect performance
 - o 5 solder pastes show somehow acceptable performance
 - o 5 solder pastes show unacceptable performance
- Printability
 - o Many pastes show comparable printability to the tin-lead reference
 - o Wear of paste improves the printability
- Wetting
 - o OSP results in wetting ratio of approximately 1.0
 - o Immersion gold wetting ratio is in the range of 1.1 to 1.7
- Overprinting
 - o Ability to overcome overprinting is perfect in all cases
- Solder ball formation
 - o By reflow on non-wetting epoxy substrate in all cases is perfect completely free from solder splash/balling
- SIR test results
 - o 5 solder pastes and the reference show perfect results $>1 \times 10^4 \text{ M}\Omega$
 - o 6 solder pastes show acceptable results in the range $1 \times 10^2 \text{ M}\Omega$ to $1 \times 10^4 \text{ M}\Omega$

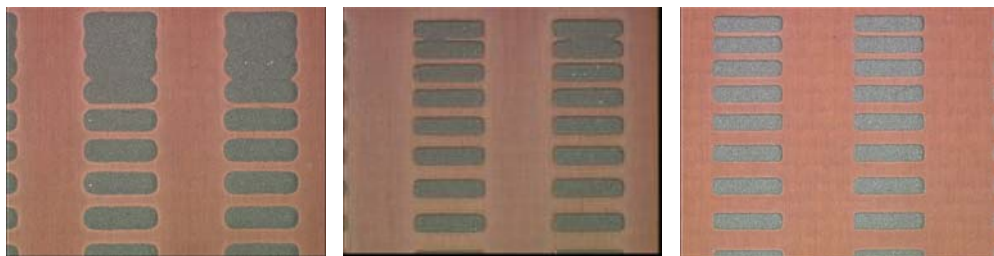


Figure 6.4 Pictures showing printability properties for 3 different pastes.

The report may be bought from SPM at <http://www.spm-erfa.dk/> . The reference is “SPM-170: 2nd generation lead free solder pastes”.

6.3 Surface finishes

Because it is important to protect the copper conductors on PCBs from degradation, PCBs are provided with finishes either with hot air solder levelling (HASL), electroless metal plating, or organic solderability preservatives (OSP). Because a fully lead-free electronic assembly will call for a lead-free finish, board manufacturers must select an alternative based on cost, reliability, and shelf life.

6.3.1 Organic Solderability Preservatives (OSP)

OSPs are a viable candidate because they are cheaper than SnPb and contain no lead. These finishes are also easily processable, relatively free of ionic contaminants, and are smoother than HASL. They also have good solderability and are reworkable.

These finishes are known for their short storage life but manufacturers may not see this as an issue. There are also concerns with handling of these finishes, durability with higher soldering temperatures, and flux chemistries used.

6.3.2 Lead-Free Hot Air Solder Level (HASL)

There is lead-free HASL available for PCBs, but some manufacturers may choose to move away from this process. If chosen, alternative HASL finishes will most likely work well with most alternative alloys and will wet faster than plated finishes or coatings. Concerns with this finish include warpage due to higher processing temperatures and PCB absorbed process chemistries.

6.3.3 Electroless finishes

There are two different types of electroless finishes: autocatalytic and immersion coatings. *Autocatalytic finishes* are achieved by adding a reduction agent to the plating bath, e.g. hypophosphite. The two most used autocatalytic coatings are Ni and Pd. In addition, Ag has recently been tested by IVF with good result.

Immersion finishes are based on an exchange process. If e.g. immersion Au is plated on Ni, Ni atoms on the surface are replaced by Au atoms. The process ceases when the whole surface is coated with Au. Common immersion finishes are Au, Ag, and Sn. Immersion Au is usually applied on top of Autocatalytic Ni and Pd as protection against oxidation. Electroless Ni/Au is attractive because of its 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.

Immersion finishes have been considered as one replacement for HASL because of its surface flatness and ease of process. Concerns must be raised regarding the thinness of the coating and shelf life since e.g. Sn/Cu intermetallics grow about 1µm/year and the intermetallic is not solderable.

6.4 Flux system

Lead free solders are in many cases known to show a somewhat reduced wetting ability compared to tin-lead solders. In order to improve the wetting properties, development of the flux chemistry is a key issue in the aim of providing state-of-the-art lead free materials, solder paste, solder wire and wave soldering fluxes. The higher process temperature also requires modification of the fluxes since there is otherwise a risk that the flux is burnt off before it is activated.

DTC, Danish Toxicology Centre is involved in the toxicology studies of all lead free and reference materials included in the MST lead free project supported by the Danish Environmental Protection Agency. Full materials specification have been provided and used in the evaluation of the human toxicology effects of the selected materials, although the precise chemical formulation of the products still is confidential to third party.

The fluxes in general consist of a blend of rosin and modified rosins, solvents, waxes, antioxidants and activators. Due to the nature of the chemicals used, skin contact during handling of flux and solder materials may irritate the skin and in some cases cause development of skin allergies and some of the chemicals may also be problematic in other respects. This is in many cases also true for fluxes used for tin-lead soldering.

As the lead free processes require higher processing temperatures, the tendency of chemicals to become airborne increases. As a consequence the use of lead free solders will possibly lead to an increase in evaporation from fluxes compared to tin-lead soldering.

In general, regarding the fluxes, the concentration of activators and antioxidants seems to be higher in fluxes used in connection with lead free solder as compared to fluxes used in tin-lead solders. High level of activators, typically organic acids, salts and halogen compounds are of potential concern, in connection with the insulation resistance properties and risk of corrosion caused by aggressive flux residuals. Careful material selection and qualification are recommended.

Initial trials in lead free soldering indicate that somewhat more flux is needed compared to standard no-clean tin-lead soldering especially by wave soldering. In this respect, the need of printed circuit board flux cleaning may become an issue.

6.5 Component requirements

According to the roadmap by Soldertec (<http://www.lead-free.org/>) all components should be lead free in EU at the end of 2004. This is probably true only for the larger component manufacturers.

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. The most common alloys used in today's component technology are still tin-lead. Alternative lead-free component finishes applied today include pure Sn (matte tin), Ni/Pd, Ni/Au, and SnCu as the most widely used plating materials. The trend in development of future lead free components goes in the direction of more extensive use of pure tin or tin alloy based component finishes. Whiskers formation in relation to the introduction of pure tin component finish is of potential concern, but still process improvement and careful control seems to have overcome this issue also for very fine pitch components. Whisker formation has been investigated in a joint project by Philips, ST, and Infineon. Information is available on the website:

http://www.semiconductors.philips.com/acrobat_download/other/green_roadmap/tin_whiskertests.pdf

In lead free soldering the component resistance to solder heat is a key issue and a potential major concern. In general, the new resistance to solder heat requirement guideline is for *worst case* a maximum temperature of 260°C, and soldering time over melting temperature of at least 60 s. This is known to be in conflict with the present practice and the performance of a number of potential sensitive component types, setting focus on the component specification and selection issue.

With moulded components concerns must be raised regarding "popcorning" and package delamination due to excessive solder heat. Also the sealing properties of hermetic and semi-hermetic components can be expected to be critical in relation to impact from solder heat, as in the cases of epoxy sealed foil capacitors, cost attractive relays etc.

In semiconductor packaging, lead free die bumping, and package balling, the use of balls formed with solder from the SnAgCu family seems to be a possible solution. Also SnAg components are available. If this path is chosen concerns need to be raised regarding the effects of high-temperature solders on the substrate and warpage of BGAs.

See B&O case (Section 9.1) for a review of "problem components".

6.6 Printed boards

Removal of lead from the process will in general lead to higher process temperature that has to be considered for printed board selection. Generally materials such as rigid boards (FR-4 and CEM) will not be more seriously affected in wave soldering compared to tin-lead wave soldering because of the short exposure time to the molten solder on the wave side.

For reflow soldering, with the higher reflow temperature, there is an increased risk of bending of the board which can cause fall off of components in the second reflow cycle in double sided mounting. If several reflow soldering processes are applied, it is advisable to evaluate the

situation. A possible remedy could be to use a support in the middle of the board*. This, however, requires component free areas where the support contacts the board. Higher T_g laminates are available but at elevated cost.

For flexible substrates the increased temperatures may be critical, e.g. affecting the choice of the plastic film.

* “Lead Free Assembly & Soldering Workshop”, presentation by Bob Willis at the Swedish lead free project (AIS-18) meeting, February 6, 2001.

7. Process qualification

This chapter discusses issues to be addressed when changing from a conventional lead-containing soldering process to a lead-free process. Process steps addressed are screen printing, assembly, reflow soldering, wave soldering, inspection, hand soldering, rework and repair.

7.1 Screen printing

In general, there are no differences in the screen printing process for lead-free solder pastes as compared to SnPb.

Tests performed by IVF included five SnAgCu solder pastes from different suppliers and two different screen thicknesses, 127 μm and 150 μm . The conclusion was that all the five solder pastes behave similar to SnPb-solder. There is a small start-up time (< 10 PCBs) before the solder paste is rolling satisfactory. Apertures in the screen were clean and the printing result was acceptable. The screen was also easy to clean after use.

National Physical Laboratories, NPL, in the UK have performed several tests of screen printing with lead-free solder pastes, both with squeegees and closed systems, like Proflow. The tests showed that there is no big difference of screen printing with SnPb-solderpaste compared to SnAgCu*.

7.2 Assembly

Assembly of 160 PCBs at IVF printed with SnAgCu-solder paste did not show any significant difference compared to assembling on SnPb-paste. Test of a waiting time of an hour between printing and mounting gave no visible decrease in assembly quality.

7.3 Reflow soldering

The key issue of soldering with lead-free solder paste is the higher melting temperature. SnAgCu has a melting point of 217°C (eutectic Sn_{3,8}Ag_{0,7}Cu) while SnPb-alloy melts at 183°C.

Most lead-free solders have higher surface-tension than SnPb solder, which means that the solderability is not as good for SnAgCu solder as for SnPb solder. The time over the melting point for the solder has to be longer to give a good reflow, i.e. an acceptable quality of the solder joint. In order to improve the wetting properties, development of the flux chemistry is also a key issue. Components self centre nearly as well in SnAgCu solder, however, as in SnPb solder according to tests performed at NPL*.

The peak-temperature during reflow has to reach at least 240°C, to be compared to 220°C for SnPb solder. The process window in reflow decreases from exceeding the melting temperature by 30-40°C for SnPb solder to 20-25°C for SnAgCu solder. This implies that there is a risk that you lower the confidence of receiving a total wetting on the PCB.

*Presentation at the SMART GROUP lead-free seminar by M. Wickham, February 15, 2001.

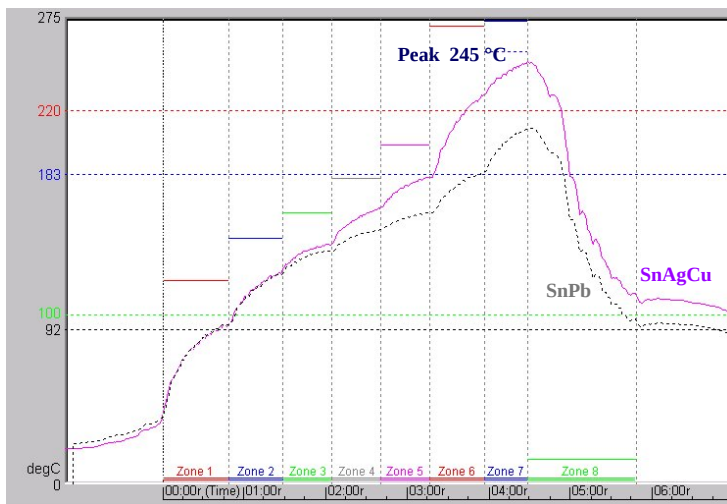


Figure 7.1 A normal temperature profile for reflow of SnAgCu solder and SnPb solder respectively.

The smaller process window is a result of minimizing the over temperature to avoid damage on sensitive components. A general recommendation is to extend the time of temperature over melting point instead.

The higher process temperature means that IR-ovens will probably not be able to manufacture good quality solder joints on complex (massive) PCBs. IR-ovens often display larger temperature-variations which result in larger temperature differences between different components on the board.

As is the case when using SnPb solder, it is strongly recommended when reflowing SnAgCu solder pastes to build the temperature-profile in the oven according to the solder-manufacturers recommendations. Naturally you have to have heat-sensitive components on the PCB in mind when programming the oven. In the Swedish lead free project, although the process window is narrower for lead-free soldering than for SnPb, the same temperature-profile could be used for all five solder pastes and still be well within the manufacturers recommendation (see Figure 7.1). It must be noted, however, that these tests were exploratory and if optimization is desired the profile has to be optimised for the paste used, component types, board type, etc.

7.3.1 Nitrogen or air?

One open issue regarding lead-free soldering is the use of nitrogen in reflow. Nitrogen gives shorter wetting time, better wetting (appearance) and fewer voids (inclusion of gas) in the solder joint. Measurements with SnAgCu solder performed by NPL showed that nitrogen decreases the wetting to half the time needed for wetting in air*. This means that the time for temperatures over melting point can be shortened by the use of nitrogen. When manufacturing simple standard PCBs, however, N₂ is probably not necessary to get good solder joints. See also section 7.4 for an investigation of the influence of residual oxygen on wave soldering.

* Presentation at the SMART GROUP lead-free seminar by M. Wickham, February 15, 2001.

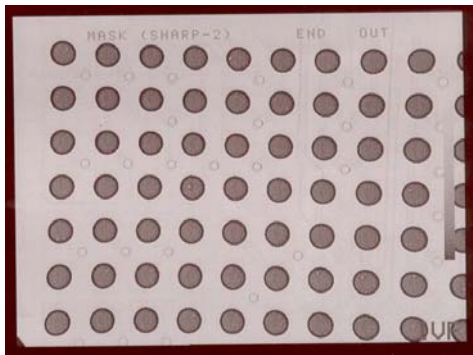


Figure 7.2 X-ray micrograph of BGA bumps reflow soldered in air.

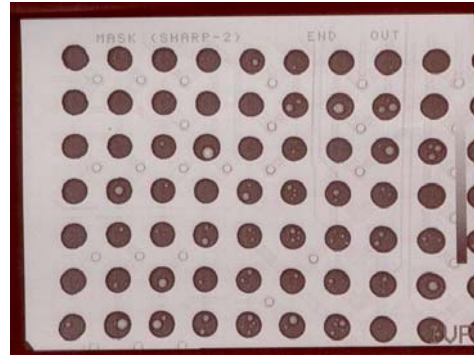


Figure 7.3 X-ray micrograph of BGA bumps reflow soldered in nitrogen.

Figures 7.2 and 7.3 above show the effect of nitrogen in one specific case with SnAgCu solder. The number of voids is much less and the size of the voids is smaller when nitrogen has been used in reflow soldering.

7.3.2 Power consumption of reflow oven Rehm v7

The higher reflow temperature for lead-free solders means that, with other factors unchanged, higher power is needed to maintain the oven temperature compared to conventional tin-lead reflow. To quantify the difference for tin-lead and lead-free reflow, an investigation was performed where the power consumption was measured from cold oven to operating temperature for two typical reflow profiles (shown in Figure 7.1).

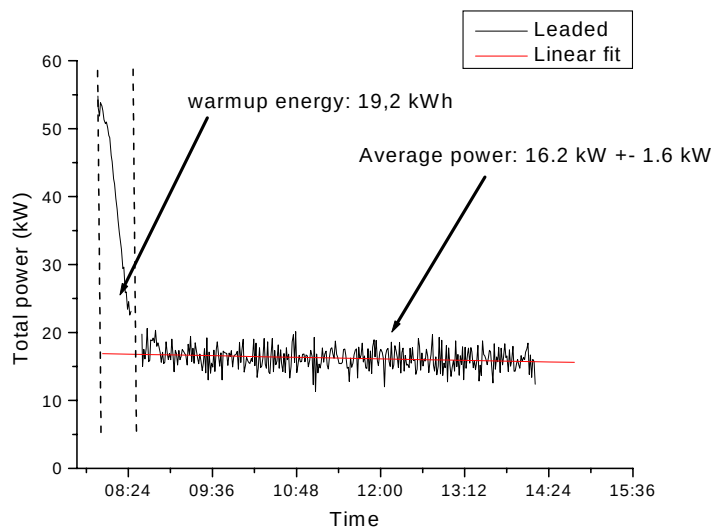


Figure 7.3. Power versus time for heating a cold oven up to operating temperature followed by six hours at tin-lead reflow temperature. For the start up 19,2 kWh is used and the average power consumption at operating temperature is 16,2 kW $\pm$ 1,6 kW.

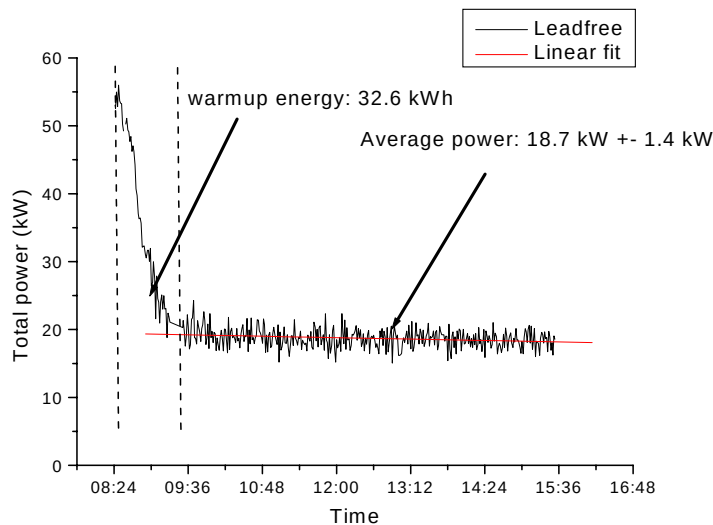


Figure 7.4 Power versus time for heating of cold oven up to operating temperature followed by six hours at lead-free reflow temperature. For the start up 32,6 kWh is used and the average power consumption at operating temperature is 18,7 kW $\pm$ 1,4 kW.

Figures 7.3 and 7.4 show measured power versus time for the two cases. To heat the oven, 19.2 kWh and 32.6 kWh is used for leaded and lead-free profile respectively, an increase of 70 % for the lead-free case. During operation an average power of 16,2 kW and 18,7 kW was measured, corresponding to about 15% higher average power consumption for the lead-free case.

7.4 Wave soldering

Candidate lead-free solders for wave soldering are SnAg3.8Cu0.7, SnAg3.5, SnCu0.7 and related alloys. Melting points for these alloys are 217°C, 221°C and 227°C, respectively. Tin-silver-copper is recommended as a multipurpose alloy for wave soldering, but both tin-silver and tin-copper could be good alternatives. The tin-copper alloy is cheaper and may be considered for low-cost products.

In wave soldering the interaction between the PCB, flux, solder alloy and processing equipment must be considered and optimized for each product. Specification of typical wave solder parameters as solder bath temperature and flux system will vary, and some values will give good performance for some products and equipment, and cause problems for others.

It is recommended to use a solder bath temperature between 250°C and 260°C, with 250°C as an absolute minimum. Tests performed in the Norwegian lead-free project shows acceptable or good results at 250°C, 255°C and 260°C, both for tin-copper alloy and tin-silver-copper. The preheating is more critical than for conventional wave soldering, and it is recommended to optimize the temperature profile with the use of top and bottom convection heating, especially for complex boards with heavy components. A typical temperature profile for lead-free wave soldering is shown in Figure 7.5 below.

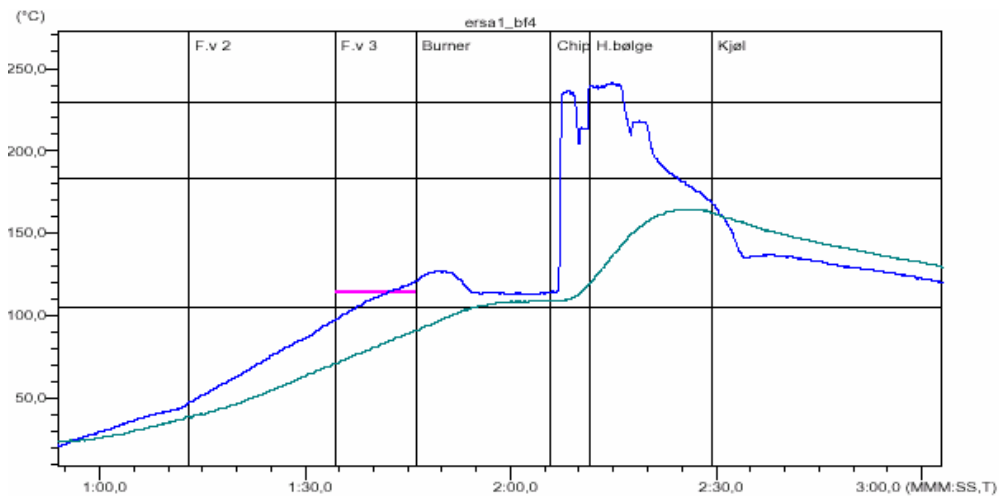


Figure 7.5 Typical temperature profile for lead-free wave soldering. This profile was developed for tests with a tin-copper alloy in the Norwegian lead-free project. The curves show board temperature during wave soldering. The upper curve is temperature at the board side closest to the wave, lower curve at the opposite side.

One effect that is present in tin-lead wave soldering but becomes a problem in the lead-free wave soldering process is the growth of an oxide layer on top of the wave. This problem could possibly be solved by phosphorus doping (patent pending) of the alloy. The use of nitrogen atmosphere will also prevent the growth of an oxide layer and the dross formation in the process. As an estimate, the dross formation doubles for every 10°C rise in temperature during soldering. Lead-free wave soldering will typically have a temperature rise of 25-30°C compared to conventional wave soldering. Thus the dross formation will be up to 8 times higher for the same atmosphere. An observation from the Swedish lead free project shows, that with other conditions being identical the atmosphere has an even more dramatic influence on the dross formation. In Figure 6.5 below the difference in wave oxide is shown and a difference in dross formation of a factor of more than 80 was observed for air compared to N₂. This could lead to the conclusion that inert atmosphere gives the best overall economy for the process. Alloy economy aside, the stability of the process increases dramatically when using nitrogen.

Another consideration with lead-free wave soldering process is the equipment. Firstly, the solder pot material should be investigated due to the fact that solder pot materials designed for conventional tin-lead soldering will dissolve into the lead-free tin-silver-copper alloy. It is therefore recommended to use more corrosion resistant stainless steel materials or a pot with a ceramic coating. The same effect could be seen on nozzle materials, and this equipment should also be considered exchanged.

The copper content in the solder bath will increase during use due to the fact that copper will dissolve from the boards into the solder bath. It is therefore recommended to periodically inspect the copper content in the bath and use either pure tin or a tin-silver alloy as top-up alloy. Before all lead is removed from PCB-finishes and component terminations, lead will also dissolve into the lead-free solder bath. The lead-content should therefore also be controlled and kept to a minimum. The safe upper limit for lead-content, however, is not yet established. Lead levels above 1% should certainly be avoided.

(a) Air

(b) N₂

(c) 5.5h 467g



(d) 72 h 72 g

Figure 7.6 The effect of N₂ and air on the dross formation in wave soldering. In (a) and (c) the soldering is performed in air. In (b) and (d) the residual oxygen level is 20 ppm. The detrimental effect on the wave is clearly visible when comparing (a) and (b). The accumulated dross is about 85 gram/hour (c) and 1 gram/hour (d) for air and N₂, respectively..

During the introduction period of lead-free wave soldering in the production, both lead-free and conventional soldering processes will be run. It is not recommended to use the same wave soldering machine for both processes, but as a minimum measure different solder pots should be used to avoid mixing of lead-free and lead-containing solder.

The conclusion is that wave soldering using tin-silver-copper, tin-silver, or tin-copper is feasible, but current materials and soldering machines may require modifications and process parameters should be optimized.

7.5 Thermal simulation of wave soldering

Thermal simulation of wave soldering is studied on a problem defined from the Lövånger-case (see section 9.5). Due to a very thick board, it was very difficult to achieve good flow into the through-holes for the components. One way of tackling this problem is to study the effects of varying different parameters in thermal simulations.

Problem definition

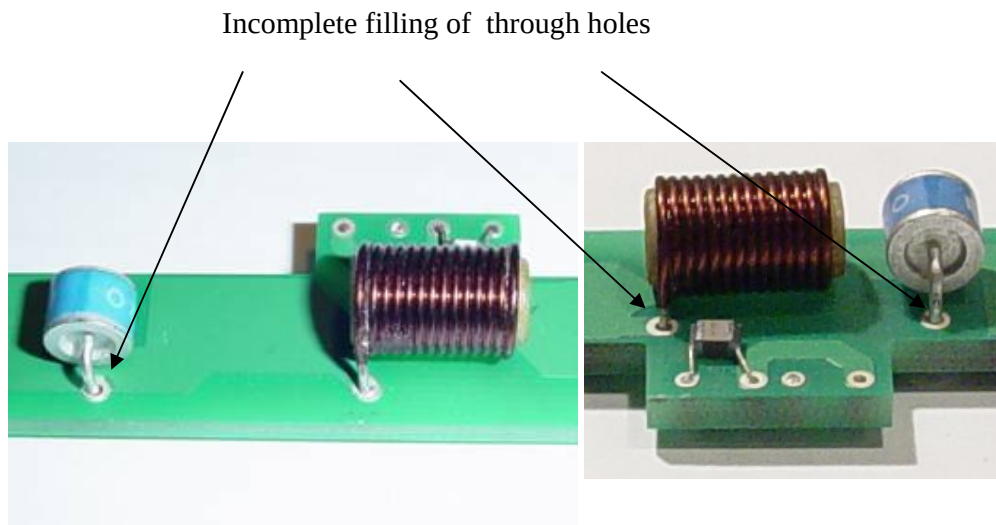


Figure 7.7 Problem definition of thermal simulation

Factors influencing the solder flow into through hole in wave soldering

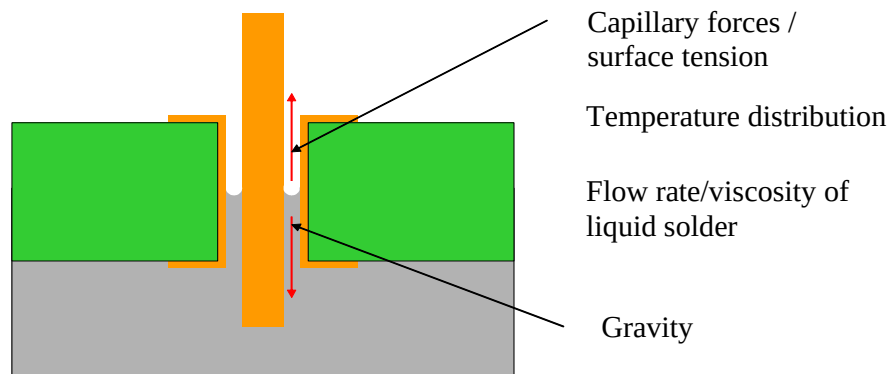


Figure 7.8 Factors influencing the flow into the hole

Effects of capillary flow and solder viscosity

In a preliminary study it was estimated that the capillary forces are strong enough to ensure capillary flow of liquid solder into a typical through hole joint. If the wetting is good and temperature is high enough there are no problems concerning capillary flow. Decreasing the gap between the pin and via hole increases the capillary force. If the pin is not located in the centre of the hole, capillary force is larger on the side of smaller gap. In the previous study it was also shown that the viscosity of the solder material is not a critical factor for the capillary flow. The time interval needed for flow filling the gap is in the order of a millisecond or less.

The effects of temperature on wave soldering

The temperature distribution is the most important factor affecting the soldering process. The temperature must be high enough to allow the flow of molten solder into the critical joint areas. The time profile must be long enough to allow the wetting of the critical areas of the joints. The maximum temperature of some components is limited which puts restrictions on the time spent in the wave.

In wave soldering the dwell time t depends on the velocity and on the length of the solder bath l according to the equation:

$$t = \frac{l}{v}$$

Requirements and simplifications for thermal simulations of wave soldering

Dynamical effects must be taken into account in thermal simulations. The heat input can be simplified by assuming a fixed soldering temperature at the bottom of the PCB for a given time period (= dwell time) and the effects of preheating can be added by assuming an initial fixed temperature (e.g. 100°C or 150°C) for the whole assembly. The simulation of the capillary flow of solder simultaneously with the thermal simulation is extremely difficult and therefore no material flow has been simulated and the geometry has been assumed to be fixed in each thermal simulation. Heat transfer by radiation has also been neglected in the simulations. The temperature of cooling air has been assumed to be 30°C.

Thermal simulations of through hole solder joints

Flowtherm thermal simulation software has been used to study thermal simulation of a typical solder joint. Simulations have been made for:

- steady state conditions as well as for transients of different time scales
- three different component materials
- three different pin diameters (0.5, 0.7 and 0.9 mm)
- different metallization thicknesses of the through hole

For simplicity the pin and through hole have been assumed to have square cross sections. The effects of element grid on the results have not been studied systematically.

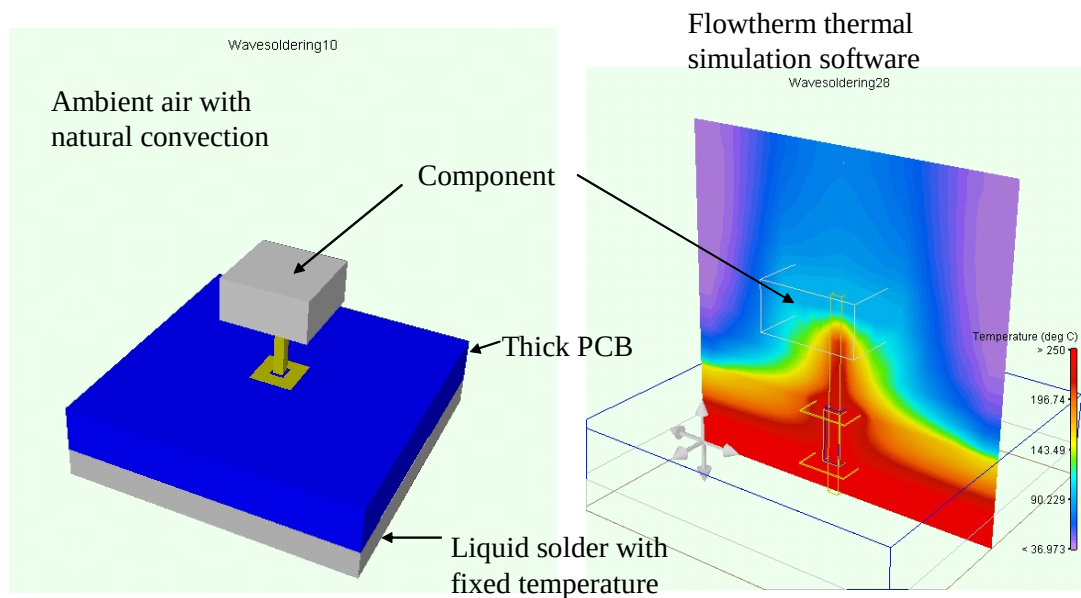


Figure 7.9 Thermal simulations of through hole joint in a thick PCB

Parameters used in thermal simulations

- Solder material Sn96.5/Ag3.5, soldering temperature 250 °C (260 °C)
- Preheating: 150 °C for some simulations
- External ambient temperature 30 °C
- Air flow: natural convection, gravity down in the pin direction
- PCB/component distance 5 mm
- PCB thickness 3.2 mm
- PCB metallization 70 mm copper in the via and on the pads (via metallization alternatives 9, 35 mm or 140 mm)
- Hole diameter 1.0 x 1.0 mm square cross section
- Pad dimensions 3.0 x 3.0 mm square on top and bottom surfaces
- Pin: copper with 0.7 x 0.7 mm square cross section (alternatives 0.5 x 0.5 mm and 0.9 x 0.9 mm)
- Component: 6 x 6 x 3 mm, ceramic, epoxy or copper

Simulation results

The next figures show some of the results achieved with the simulation software.

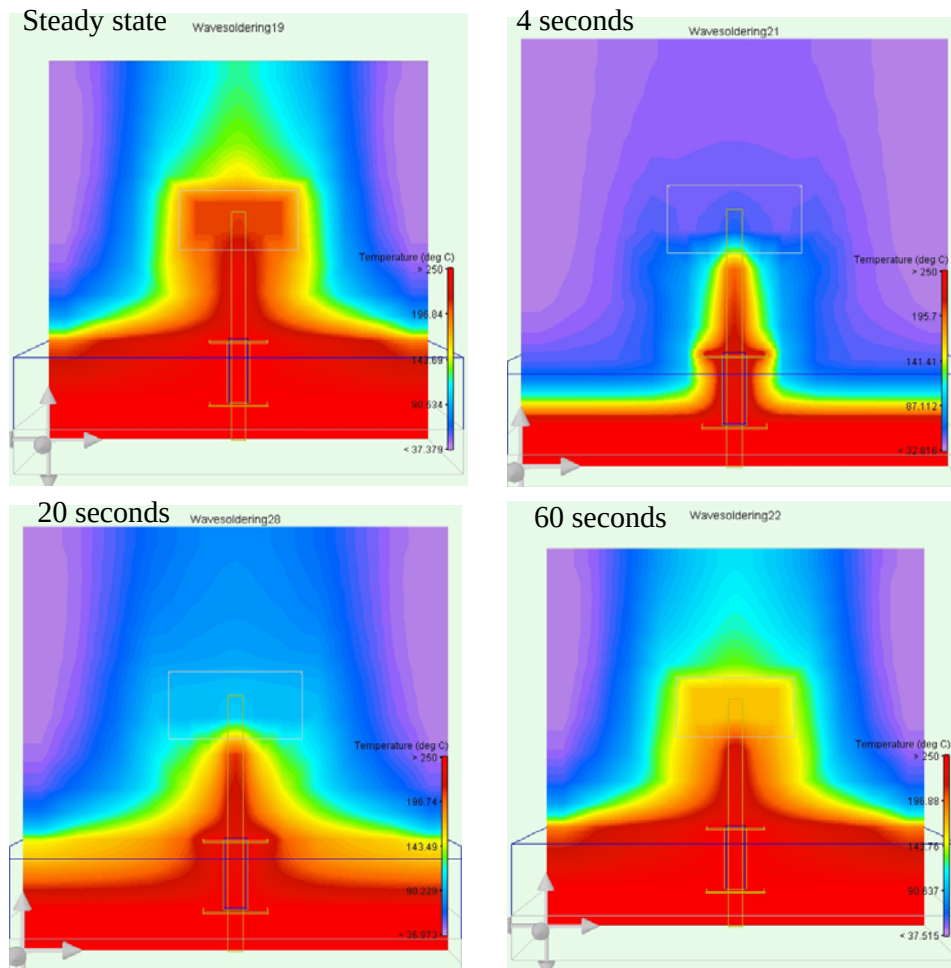


Figure 7.10 Evolution of thermal profiles for the through hole solder joint for different times after applying the wave soldering temperature 250 °C onto the solder bath below the PCB

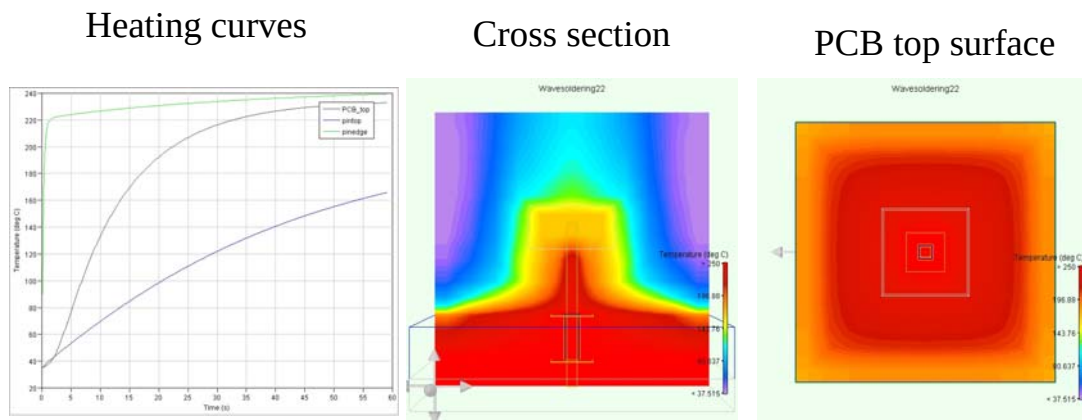


Figure 7.11 Thermal profiles after 60 s heating transient for the case of component with thermal conductivity of alumina ceramics

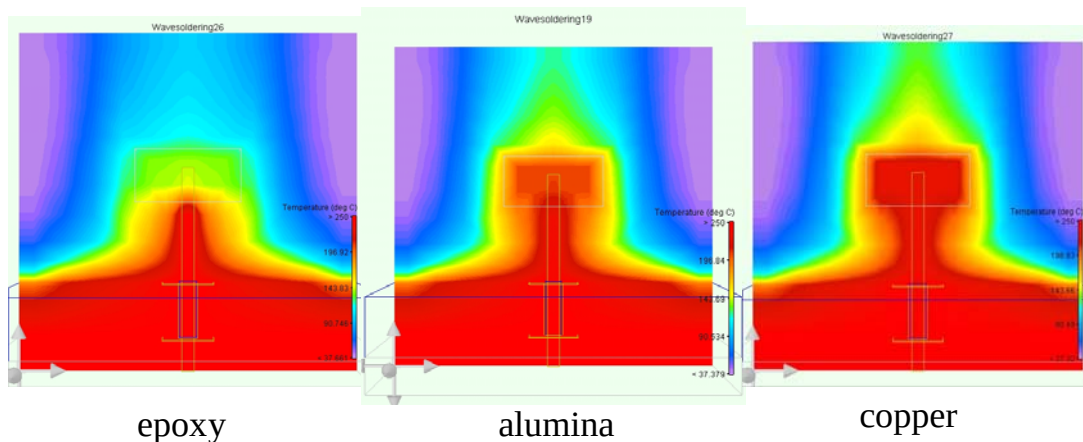


Figure 7.12 Effects of component material on steady state temperatures

Effects of preheating

In the first set of simulations the initial temperature before the wave soldering was assumed to be at an ambient temperature of 30°C and the soldering temperature was 250°C. In further simulations the effects of preheating were approximated by assuming an initial temperature of 150°C and a slightly higher soldering temperature of 260°C was assumed. It is seen that the preheating has a large influence on the simulated temperature distribution.

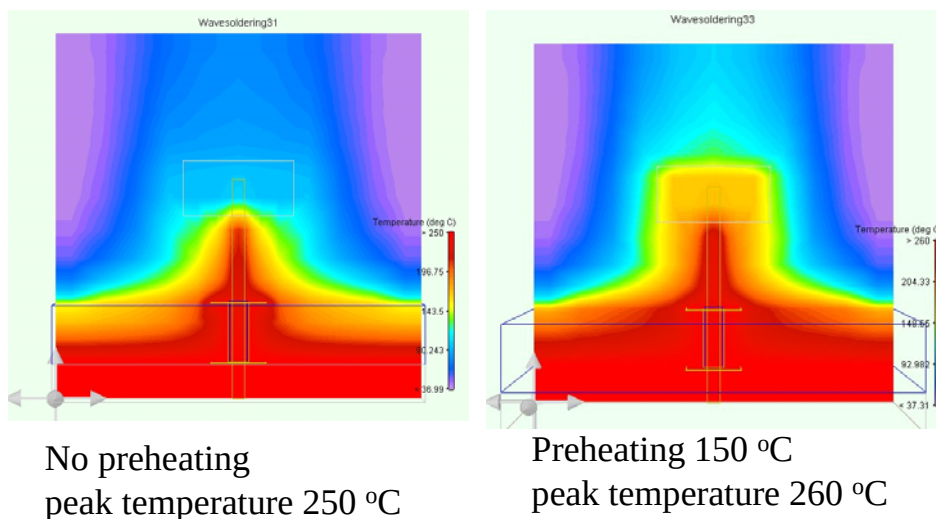


Figure 7.13 Effects of preheating

Effects of pin diameter

Three different pin diameters have been used for the hole diameter of 1 mm. The diameters used in simulations were 0.5 mm, 0.7 mm and 0.9 mm. The main effect of the pin diameter is on the temperature of the component. The increase of pin cross section area increases the heat conduction along the pin and leads to higher component temperatures. To avoid excessive heating of components thinner pin cross section is beneficial. The decrease of pin diameter from 0.7 mm to 0.5 mm decreases the temperature of component from 173°C to 160°C. Increasing the diameter

to 0.9 mm increases the temperature up to 186°C. The pin diameter seems to have a smaller influence on the temperature at the level of PCB surface (pin edge temperature)

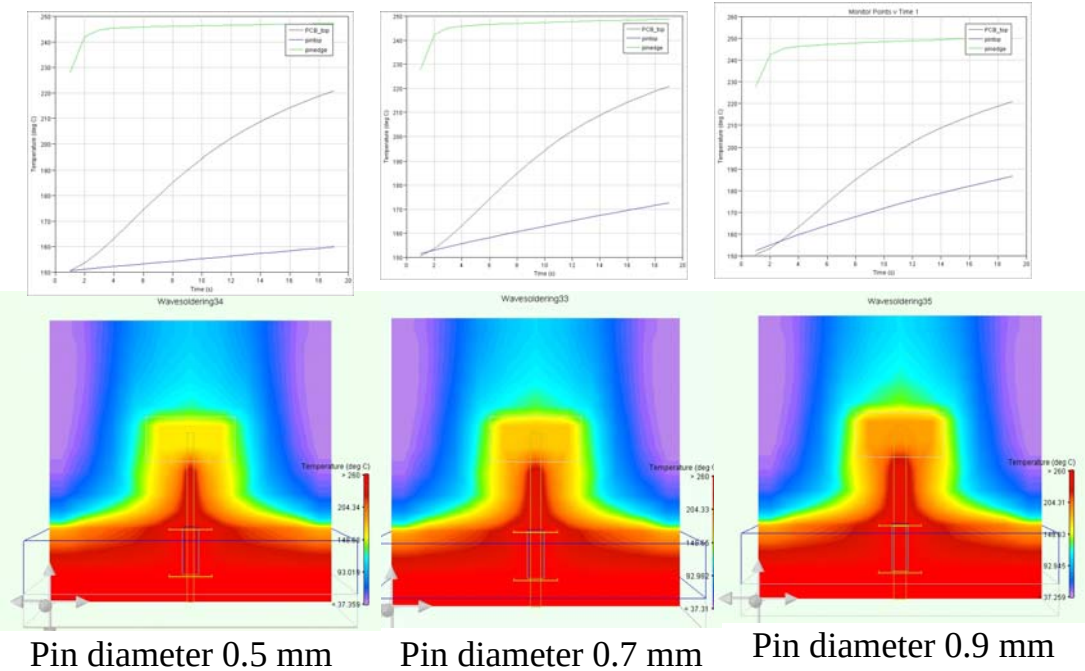
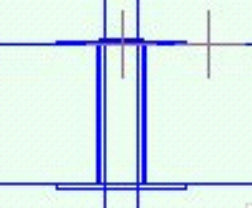


Figure 7.15 Effects of pin diameter

Effects of metallization thickness in the hole

In previous simulations the metallization thickness was assumed to be 70 µm for the via holes as well as for the collars of the via hole. For the simulations with the new soldering profile, metallization thickness was also varied having values 9 µm, 35 µm, 70 µm and 140 µm. The differences in temperature distribution are quite small for this range of thicknesses. The top pad average temperature decreases by 2.1°C by decreasing the metallization thickness to half of its original value and by 10.6°C when the metallization thickness decreases to 9 µm.

Table 7.1 Effects of metallization thickness in the hole

	Metallisation thickness µm	Top pad temperature °C
	9	244,9
	35	253,4
	70	255,5
	140	256,7

7.5.1 Summary of the thermal simulations of wave soldering

- The thermal effects of wave soldering can be simulated assuming fixed temperature for the liquid solder on bottom of the PCB for a time period of the dwell time of the soldering process
- Assumption of fixed geometry for the solder joint seems to be justified
- Transient dynamical effects are important for the simulations
- Preheating has a large influence on the temperature distribution
- Thermal properties of the component seem to have a strong influence on the temperature distribution
- Pin diameter has a quite large effect on the temperature of the component but has only minor influence on the temperature distribution in the joint itself
- Thickness of via metallization has an influence on the temperature distribution in the solder joint area

7.6 Inspection

A solder joint of SnAgCu has a more greyish and matte appearance when compared to a SnPb solder joint as shown in Figure 7.16.a below. Also the geometry of the solder joint differs somewhat from SnPb due to the lower wetting ability. SnAgCu solder does not spread as well on the pad as SnPb solder. This might result in a changed standard footprint on PWBs, i.e. smaller pads with rounded corners.

The matt surface of the solder joints makes it harder for the human eye as well as for a robot to detect non-conformity in a solder joint. Instructions for operators have to be revised and the automatic inspection robots have to be reprogrammed to set acceptance criteria.

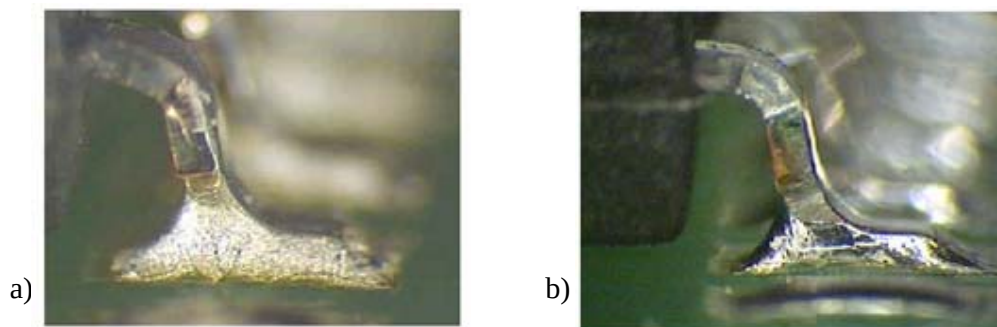


Figure 7.16 Illustration of the difference in surface finish of a solder joint between lead-free solder with a slightly grainy surface (a) and conventional solder with a shiny and smooth surface (b).

7.7 Rework and repair, hand soldering

An unresolved issue regarding production of lead-free electronics has been rework and repair due to the higher temperatures needed to create a good solder joint. There are higher demands on the equipment for lead-free soldering, both repair-robots and hand soldering stations. It is crucial to create a temperature-profile that is similar to the one used in the reflow oven. Skilled personnel report that hand soldering with lead free solders needs more time than ordinary SnPb.

7.8 Factorial test 1 - Soldering

In the Swedish lead-free project the test board shown in Figure 7.17 was used to investigate the effect of a number of process parameters on the soldering results.*

The *processes* investigated and the corresponding equipment used were:

- Screen printing – DEK 265
- Component placement – Mydata My9
- Reflow soldering – Rehm V7 with seven zones
- Wave soldering – EPM, hermetic oven

The temperature profile of Figure 7.1 was used in reflow.

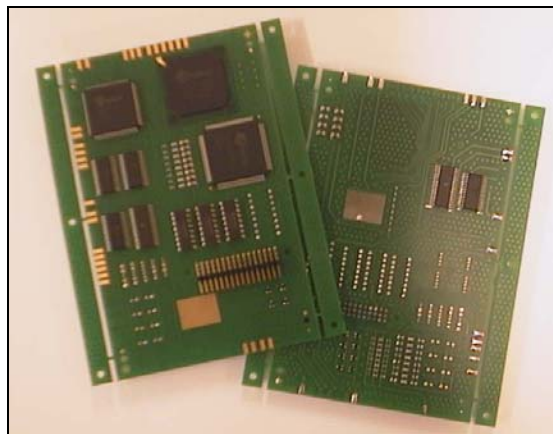


Figure 7.17 The IVF test board used in the factorial tests.

7.8.1 Control parameters (factors) and levels

The following control parameters and levels were chosen: The resin containing flux for wave soldering is optimized for lead-free process and N₂. The bath temperature was 260°C. The residual oxygen level during wave soldering was 20ppm.

* The results of SIR measurements and temperature cycling will be included in a later version of the guideline.

- | | |
|-----------------------------|-----------------------|
| • Stencil thickness | 127 µm/150 µm** |
| • Atmosphere reflow | Air/N ₂ |
| • Flux for wave soldering | resin free/with resin |
| • Atmosphere wave soldering | Air/N ₂ |

In the tests five different SnAgCu solder pastes were investigated (three no-clean and two water soluble).

With these parameters a full factorial test was performed with two replicates of each setting giving $2 \times 2^4 = 32$ boards for each solder paste, in total 160 boards. It should be pointed out that the number of solder joints per board is close to 1000.

7.8.2 Result parameters (responses) and criteria

The observables and corresponding criteria chosen for visual inspection (and X-ray inspection of BGA) that all affect the quality of a PCB were:

- **Wetting** for reflow
- **Wetting** for wave soldering
- **Cleanliness**
- **Solder balling**
- **Bridges** under the BGA (2D Xray)
- Other **bridges**

The responses have been evaluated according to the following criteria:

Wetting

- 0 Perfect result
- 1 OK but not 100% wetting on annular rings and pads
- 2 Wetting but not complete pad wetting or hole wetting, barely OK
- 3 No wetting in one or more solder spots

Cleanliness

- 0 Spotlessly clean
- 1 Acceptable flux residues
- 2 Contaminated board that customer could reject
- 3 Severely contaminated board that needs cleaning

Solder balls

- 0 Zero or one
- 1 A few scattered
- 2 Many on same component type
- 3 Many on different component types

** 150µm is often the first choice but for fine pitch sometimes 127µm is needed.

Bridges under BGA

- 0 No bridges
- 1 Bridges exist

Other bridges

Number of legs involved in bridging

7.8.3 Main effects and interaction plots

The graphs below show results for the different result parameters for all 5 solder pastes lumped together since the difference between the different solder pastes was not significant. Only significant ($\geq 95\%$) results are shown. NB that a low number is a good result. Flux 1 is resin free and flux 2 contains resin and is optimized for lead-free soldering.

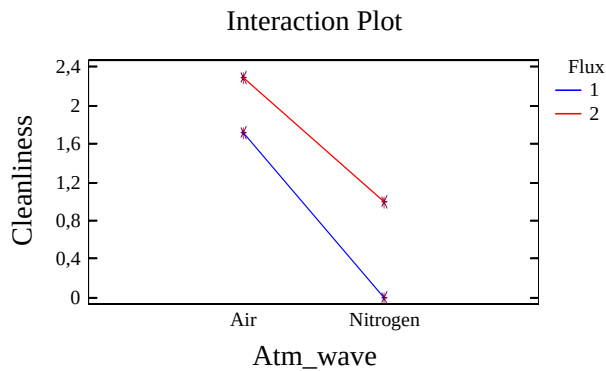
Wetting for wave soldering

Figure 7.18 Interaction plot for wave soldering. For wetting there is an interaction between the flux and the atmosphere used. Resin containing flux and N_2 gives the best result

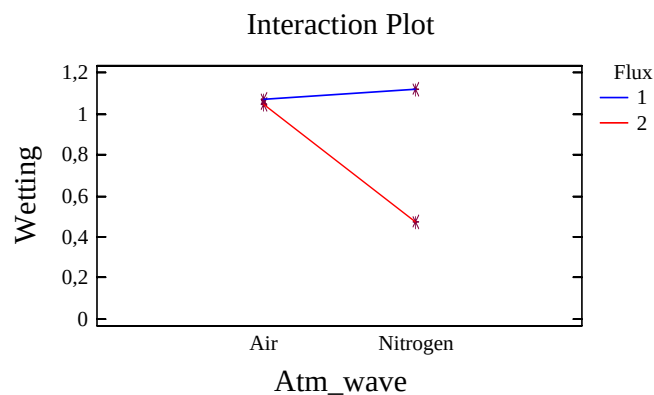
Cleanliness

Figure 7.19 Interaction plot for cleanliness and wave soldering. Resin free flux and N_2 give the cleanest boards.

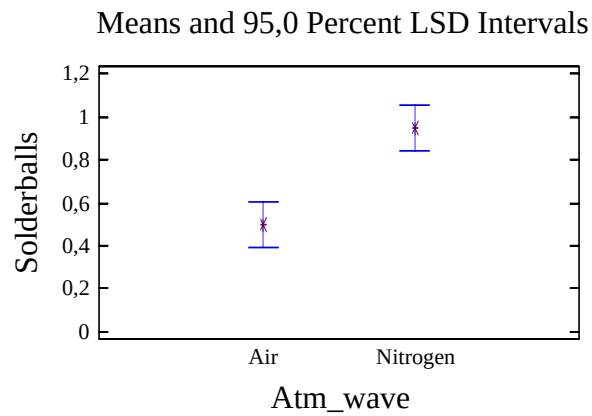
Solder balling

Figure 7.20 Main effects for solderballing in wave soldering. Wave soldering in air give less solderballs than soldering in N_2 .

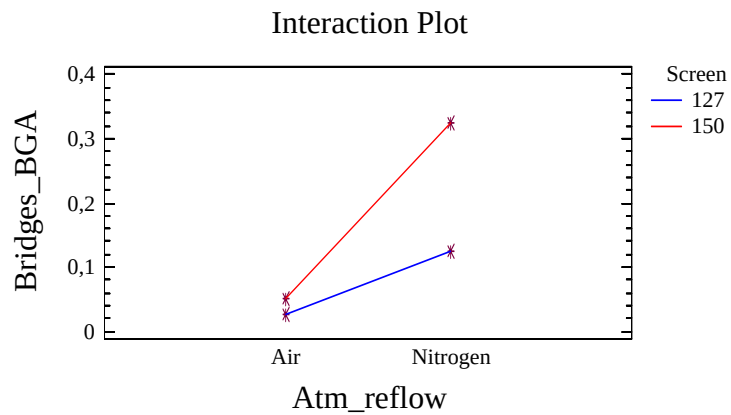
Bridges under BGA

Figure 7.21 Interaction plot for bridges under BGA and atmosphere for reflow soldering. Less bridging is observed for thin stencil and reflow in air.

Other bridges

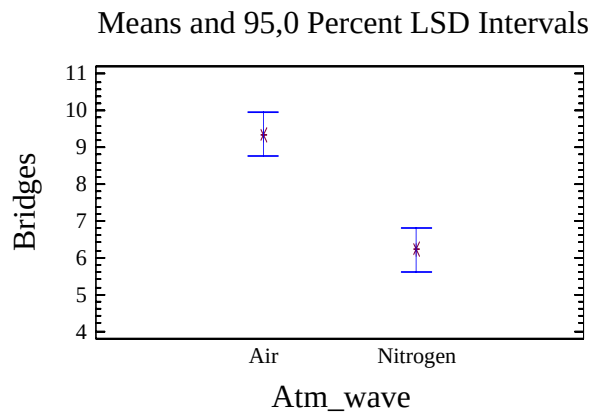


Figure 7.22 Main effect for bridges and wave soldering. Use N₂ for less bridging.

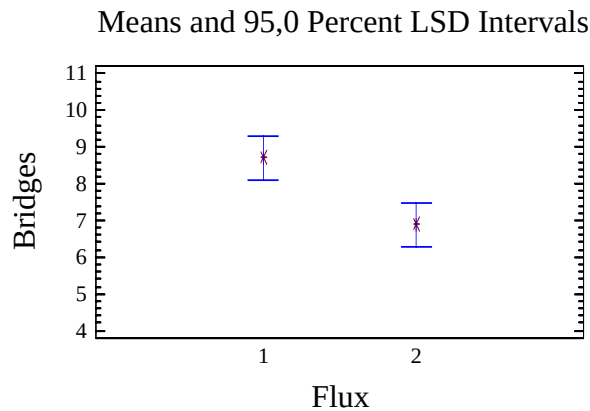


Figure 7.23 Main effects for bridges and wave soldering. Flux 2 that contains resin (optimised for lead free) gives the least bridging.

7.8.4 Main conclusions

For best results for the responses investigated the following conclusions can be drawn from the present study.

Wetting

SMT – Use N₂ in reflow

HMT – Use flux with resin and N₂ in wave soldering

Cleanliness

SMT – Use N₂ in reflow (slight difference)

HMT – Use resin-free flux and N₂ in wave soldering

Solderballs

SMT – Use thin screen and air in reflow

HMT – Do not use N₂ in wave soldering

Bridges (identical for BGA and other components)

SMT – Use thin screen and air in reflow-oven

HMT – Use flux with resin and N₂ in wave soldering

It is clear that there is a trade off between e.g. cleanliness and solder balling or wetting. In these exploratory tests the goal was to find the main effects not to optimise the processes. To optimise a particular product, however, a similar procedure can be used.

To find optimal settings a sequential design of the experiment is made. This is often referred to as RSM – Response Surface Methodology.

7.9 Factorial test 2 - The influence of residual oxygen on wave soldering

In a second test series using the same test board the influence of residual oxygen on the soldering result and on reliability was investigated.³

7.9.1 Control parameters (factors) and levels

The main objective was to investigate the influence on soldering quality of the residual oxygen levels. In addition the influence of reflow (simulation) on soldering result was investigated.

The control parameters and levels chosen were:

- Reflow simulation – Yes/No
- Residual oxygen level in wave soldering – 50 / 100 / 500 ppm

These levels were chosen after consulting experts on wave soldering. With these parameters a full factorial test was performed with five replicates of each setting giving in total $2 \times 3 \times 5 = 30$ boards.

7.9.2 Results parameters (responses) and criteria

The observables and corresponding criteria chosen for visual inspection after wave soldering were:

³ The tests were performed at IVF (Mölnadal, SE) and Heraeus (Hanau, DE) and were analyzed by IVF and ZAVT GmbH (Lippstadt, DE) by order of Linde Gas AG and AGA Gas AB.

Wetting

- 0 Perfect result
- 1 OK but not 100% wetting on annular rings and pads
- 2 Wetting but not complete pad wetting or hole wetting, barely OK
- 3 No wetting in one or more solder spots

Cleanliness

- 0 Spotlessly clean
- 1 Acceptable flux residues
- 2 Contaminated board that customer could reject
- 3 Severely contaminated board that needs cleaning

Solder balls

- 0 Zero or one
- 1 A few scattered
- 2 Many on same component type
- 3 Many on different component types

Bridges

Number of legs involved in bridging

7.9.3 Soldering result – visual inspection after wave soldering

Figure 7.24 below shows the only “almost significant” (≥ 94.8 % confidence) result of the visual inspection for the different result parameters. The Figure shows that for the occurrence of solder balls there is no difference between 50 and 100 ppm, but both give better result than 500 ppm. No conclusions can be drawn concerning the effect of residual oxygen on wetting, purity and bridging from this investigation.

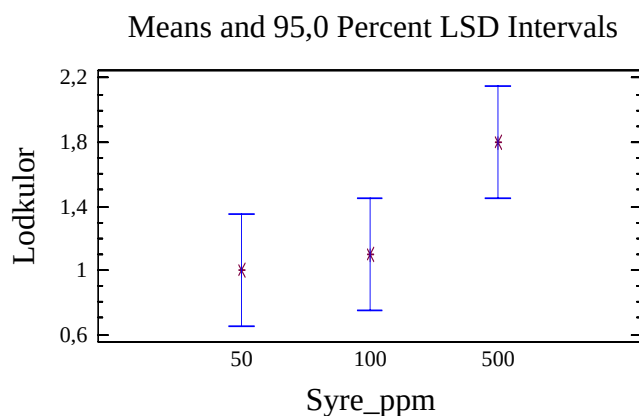
Solder balls

Figure 7.24 Effect of residual oxygen on solder balls after wave soldering (94.8 % confidence)

7.9.4 Inspection after ageing and temperature cycling

Temperature shock -40°C $-+100^{\circ}\text{C}$ with 30 minute dwell time up to a maximum of 1000 cycles and high temperature storage at 125°C for 1000 hours, respectively, were used for climate tests at ZAVT. Briefly, the following conclusions could be drawn from the investigations:

- The effect of residual oxygen is not visible after exposing the boards to these environmental tests. It should be pointed out that the number of boards is fairly low and comparison with air would be beneficial.
- The solder joints show no variation in geometry or surface quality that can be traced to the residual oxygen level.
- The number of pores is lower for SMT components (0805, SOIC32) than for hole mounted ones (DIL, connector). For 0805 a statistical analysis of the pores showed that the number of pores increased with residual oxygen level. Qualitatively the same result was found for the other components.
- After temperature shock, no effect of residual oxygen was observed. More cracks were observed for the connector than for 0805. After 1000 cycles, no cracks could be detected for SMT.

At high temperature storage, growth of intermetallic phase was observed for 0805, the rate, however, is independent of residual oxygen level

7.10 Solderability and shear strength

In the Finnish Lead-free soldering project (KOTEL/VTT) the solderability of lead-free terminated components and reflow soldered and wave soldered lead-free joints were investigated by visual inspection and shear strength measurement of chip components and compared to tin-lead joints.

Results indicate that the solderability of lead-free terminated components can sometimes be worse than for SnPb terminated components. Incomplete wetting during reflow soldering of some SMD components can occur, in this case tin terminated chip resistors reflow soldered with SnAgCu solder. Generally large differences in wave solderability of chip components are not expected for either lead-free or lead containing. Solder bridging between some wave soldered surface mount components can be larger with lead-free SMD components compared to lead containing components. In general adequate wetting of joint areas on the wave side of the board can be achieved with proper process optimisation and flux selection. Some voids have been detected in reflow soldered and wave soldered through-hole joints.

Shear strength measurements were performed before and after temperature cycling (-40°C to $+125^{\circ}\text{C}$ for 1000 hours). Variations of the shear strengths of chip resistors and capacitors were quite large after soldering and could not be specified as a lead-free material characteristic. On the whole, the joint strengths of lead-free chip components were at the same level as tin-lead joints and were thus satisfactory. The variations of joint strengths became equalized in some series after temperature cycling. Different termination plating materials of chip resistors and capacitors (100% tin and Cu/Ag/Ni, respectively) did not clearly affect to shear strengths of the components. Some examples of shear strengths are shown in Figures 7.25 - 7.27.

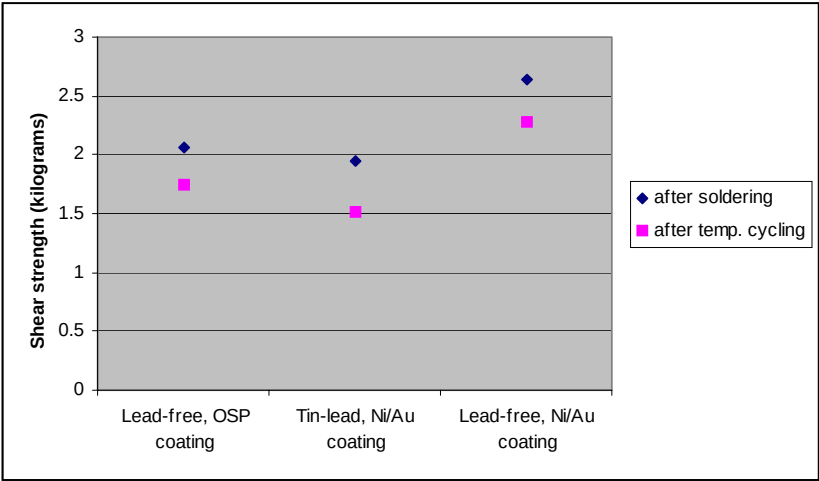


Figure 7.25 Shear strength of reflow soldered 0402 capacitors.

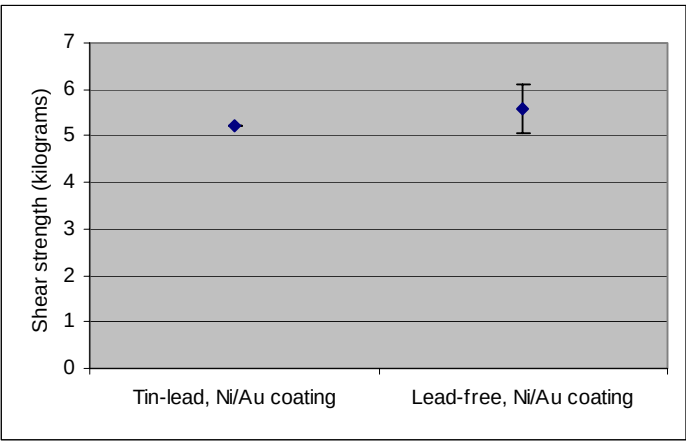


Figure 7.26 Shear strength of wave soldered 0603 resistors after temperature cycling.

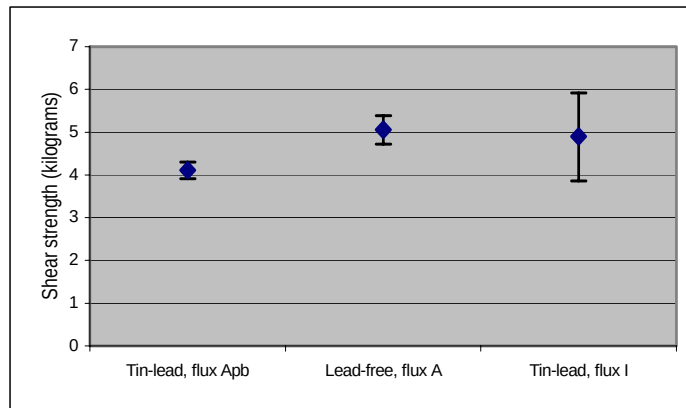


Figure 7.27 Shear strength of wave soldered 0603 resistors on CEM-1 laminate after temperature cycling. Surface finish was OSP.

7.11 Fillet lifting after wave soldering

In the Finnish project, wave soldering tests were performed both with lead-free solder and SnPb solder. For the lead-free case, fillet lifting was observed in some components as shown in Figure 7.28.

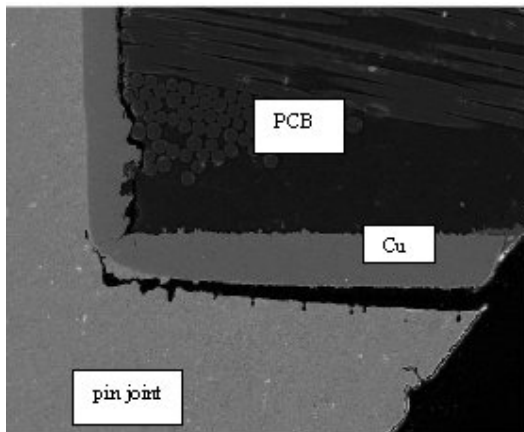


Figure 7.28 Fillet lifting from the pad after temperature cycling, the sample is wave soldered through-hole connector.

8. Reliability

Early assumption was that lead-free assemblies would have higher reliability than leaded assemblies. This was assumed because lead-free solders have higher melting points, the joints have higher strength, especially creep strength, and materials have better isotherm and bulk alloy low cycle properties. But final product relative reliability performance cannot be predicted from bulk solder alloy properties.

The high tin lead-free solders with Ag, Cu, Sb and Bi show similar reliability to SnPb solders*. Under high temperature and strain ranges, SnPb solders tend to have a higher fatigue life than the lead-free solders. Under low temperature and strain ranges, lead-free solders have up to double the fatigue of the SnPb alloys.

8.1 Reliability results from the Danish projects

On board level reliability testing of lead-free solder joints has been studied in two Danish national R&D projects in the case of SnAgCu and SnAg type replacement solders used in:

- Reflow soldering single-sided and hand soldering,
- Reflow soldering double-sided and
- Combined reflow and wave soldering.

Reliability testing, including high temperature ageing testing, temperature cycling testing and damp heat testing, has been performed. Solder joints have been examined by visual examination, X-ray examination and destructive physical analysis by micro sectioning followed by optical microscopy.

Temperature cycling testing was found to be the major accelerating factor in joint degradation, and the degradation mode in the case of the typical range of SMD joints involves degradation in the solder bulk material. Reliability performance of the lead free SMD joints is found to be similar to SnPb joints and in general acceptable performance can be expected up to more than 1000 cycles, -40°C; +85°C.

The same temperature cycling tests applied to lead-free leaded joints indicates a poorer performance of the lead free joints compared to traditional SnPb joints. Preliminary results indicate that ways of mechanical stress release in relation to the component termination are much more critical to the joint reliability in lead free hand soldering and wave soldering of leaded components, compared to SnPb soldering. This is most likely due to the higher strength of the solder material itself, leading to higher stress build-up in the solder to board finish and solder to component finish interfaces respectively.

In general, further studies are required in order to get a better understanding and improvements in lead free solder joint reliability in mixed technology printed circuit board assembly, where a range of odd-shaped leaded components can be regarded as potential trouble spots.

*Presentation by Hector Steen, Multicore at the seminar “Time to go lead-free”, IVF Mölndal, June 13, 2002.

8.2 Reliability results from the Finnish project

In the Finnish project (KOTEL/VTT) the following reliability tests were performed:

- Temperature cycling (-40°C to +125°C for 1000 hours)
- Fatigue life measurement of BGA components (bending test)
- Accelerated life test (85°C 85%RH for 500 hours, 15 volts bias)

In addition, shear test measurements were performed before and after temperature cycling (see section 6.8). The joint integrity of BGA daisy chains during temperature cycling was controlled by resistance measurements. The joint integrity of PIH (pin-in-paste) connectors was controlled after temperature cycling test from cross-sections.

As a general conclusion, lead-free and lead-containing component boards behaved similarly during reliability tests. Congruent with the conclusions from the Danish project temperature cycling was found to be the major accelerating factor in joint degradation.

The results of the bending of BGA components can be considered as preliminary. Any dramatic differences between lead-free and tin-lead BGA components against cyclic bending could not be observed. Cross-section samples showed that BGA balls were typically cracked on the component joint as shown in Figure 8.1.

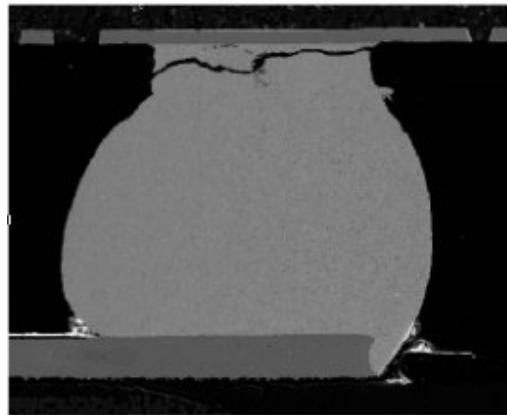


Figure 8.1 Cracking of the component was seen from the cross-section on the component side.

9. Case studies

9.1 Bang & Olufsen (DK)

Eighty-year-old Bang & Olufsen (B&O) is the last remaining member of what was once a thriving Danish radio and television industry. The company's first radio was introduced in 1926, followed by a gramophone in 1943 and the first black and white B&O television in 1952.

Today B&O is a world class company, celebrated for its high design standards, which manufactures and markets a broad range of products including a variety of hi-fi systems, integrated and stand-alone television/video recorder systems and a broad range of speakers. The company also controls a range of telecommunications and medical subsidiaries that have been spun off from the core business.

Although the company was well ahead of the industry in planning for the transition to leadfree solders, the NoNE project provided a welcome boost for the company. It has now been established that six wave solder production lines will have to be replaced in order to accommodate heavier PCBs using a tin-copper alloy, while existing foam flux systems using alcohol based fluxes will give way to water-based spray fluxing.

"With lead-free soldering, we have started all over again from scratch, says Ole Jensen, technology adviser at Bang & Olufsen in Denmark. Everything that we know has to be reconsidered. In Denmark there was only a limited knowledge of lead-free soldering, so the Nordic project, which enables us to share ideas, resources and results, is very valuable indeed!"

Making solder joints using metal alloys at different compositions is a very complex process -- but few people in the EE sector are any longer aware of that, because the old solder alloy, techniques and equipment have been used for so long and with such good results."

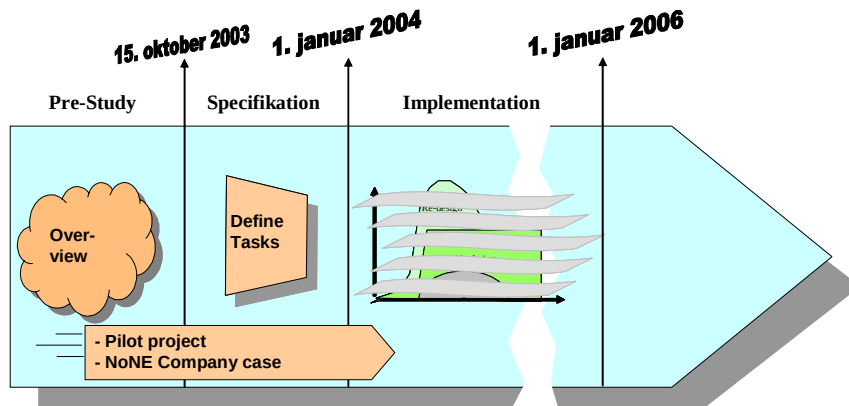


Figure 9.1 Illustration of the RoHS-project at B&O

9.1.1 B&O product case

Products for NoNE –case and RoHS pilot project



Figure 9.2 Low Power Video Output (LPVO) printed circuit board. Key parameters: 221 components total, 73 different components, 12 component suppliers, FR4: 2 layer, 1.6 mm thickness.



Figure 9.3 ICE System 1 Key parameters: 635 components total, 160 different components, 39 component suppliers, FR4: 4 layer, 2.4 mm thickness

9.1.2 B&O component strategy for the transition to lead-free

Start by building your “lead-free component basics” w.r.t. component specifications, component lead finish, resistance to solder heat concerns, and solderability concerns

The methodology consists of reviewing component data sheets w.r.t soldering process conformance concerns, e.g. wave & vapor phase soldering and lead-free soldering condition concerns, e.g. temperature and time mismatch.



Figure 9.4 Tin-lead soldered internal interconnects become critical! Example: Polypropylene foil capacitor. Soldering condition out of specification, Peak temperature specified: Max. 220 °C, Time above 180°C: Max. 60 s, Lead free condition: 235 °C, 60 s

Component lead finish

Standard tin-lead finish will be common for components during the transition period. This makes it important to know the effects of interaction between different surface finishes and solder alloys. Sn will probably be the most common surface finish but it may be necessary to analyse the component lead finish type.

Resistance to solder heat concerns

Moisture concerns

Popcorn degradation is expected to increase for IC-families. To tackle this problem, relevant simulated soldering and SAM microscopy is an important analytical tool (See ABB case for illustrative case study). The trend is that the moisture sensitivity level increases 1-2 classes. This means that component logistics is becoming more critical in lead free soldering.

Seal concerns

Rubber, epoxy & glass sealed semi-hermetic and hermetic parts have to pass lead free soldering conditions. Relevant simulated soldering followed by bubble seal testing is an important tool. The conclusions from B&O tests are that potential trouble components are electrolytic capacitors, foil capacitors, relays, and oscillators. Typical testing conditions are 85°C, 105°C and 125°C at 60 s.

Heat degradation concerns

Thermal stress induced cracking degradation may occur for ceramic multi layer chip capacitors (See Figure 9.6). To test for heat resistance hot dip testing at 260°C for 60 (or 10) s can be used followed by electrical testing, micro sectioning, and optical microscopy.

Low temperature grade plastic degradation of electromechanical components has been observed (See Figure 9.7). Simulated soldering and optical microscopy are used in pinpointing potential weak parts. Scanning Acoustic Microscopy (SAM) and/or micro sectioning and optical microscopy are important analytical tools.

Conclusions from B&O tests are that the main accelerating factors for heat degradation are

- wave soldering,
- high capacitance values vs. chip size, and
- X7R vs. NPO!

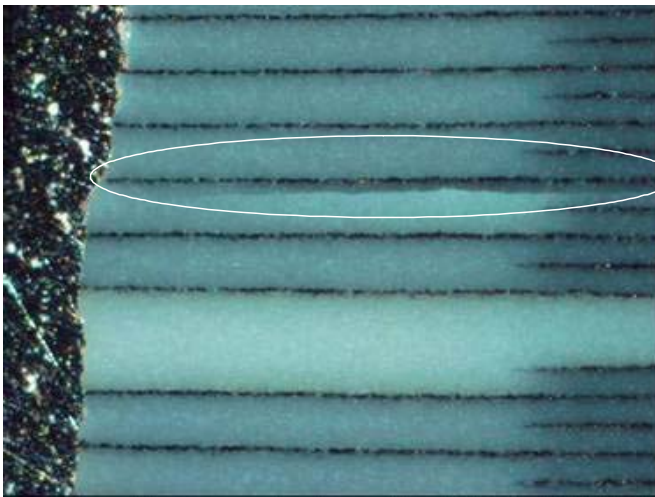


Figure 9.6 Thermal stress induced cracking degradation in ceramic multi layer chip capacitors

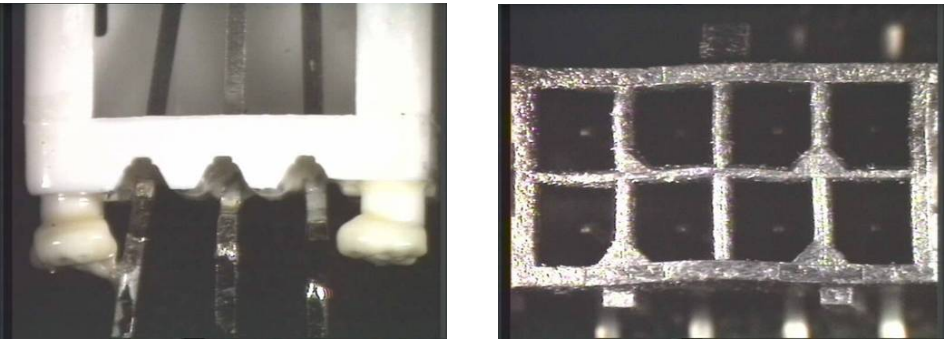


Figure 9.7 Low temperature grade plastic degradation, electromechanical components.

Cu leaching in wave soldering

Cu-leaching from component plating is of potential concern depending of the lead free alloy used (See Figure 9.8). A conclusion from the tests at B&O is that wave soldering is the accelerating factor in leaching, increasing in the order SnCu, SnAgCu and SnAg!

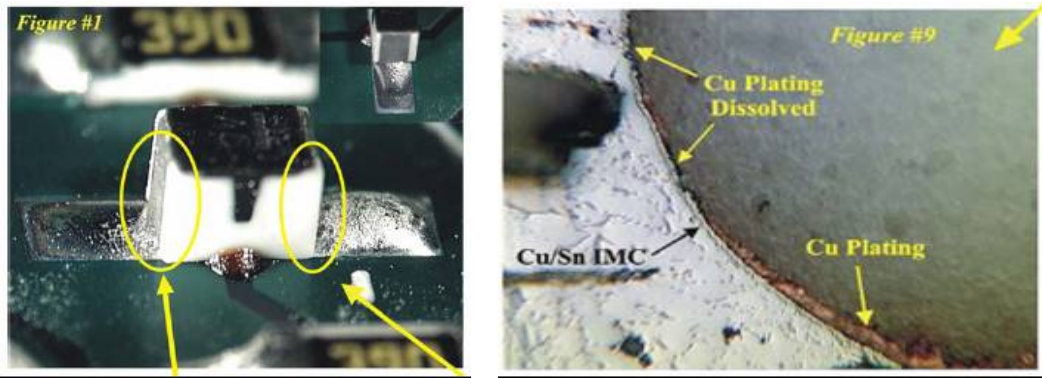


Figure 9.8 Effects of tin leaching

This was solved by modifying the plating on a SOD110C by introducing a galvanic Ni layer on top of the electroless Cu (See Figure 9.9)

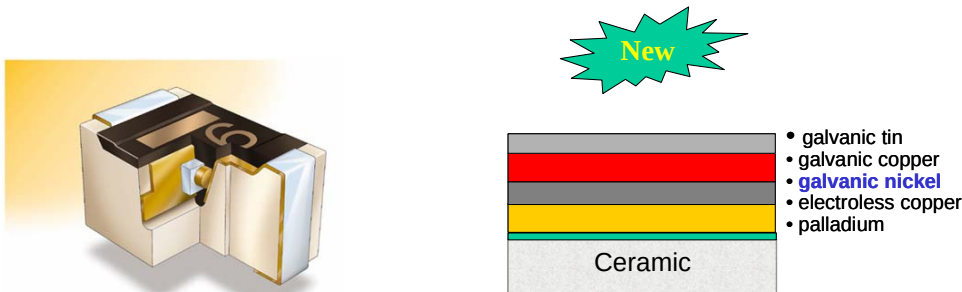


Figure 9.9 New build-up of ceramic SOD 110 package

Component review

To prepare for transition for lead-free for a product it is important to review all components. The check list shown in Table 9.1 is used at B&O to do this in a systematic manner. A questions that still is not resolved in the transition to lead-free is whether supplies will use a "running change" with supplied components or go for material number change.

Table 9.1 Example of review of components from the LPVO-board

Electromechanical components										
Family name	Group name	Type name	Identification	Manufacturer	Lead finish	Lead free concerns			RoHS Yes/No	DPA ref.
						Moisture	Seal	Heat		
Connectors	HT tube socket	Leaded body	72C01:9	J.D. Friderichsen A/S	Su	None	None	Marginal	Yes	Marginal pass, hot dip, 260 °C, 60s.
	PBC socket	SMD	7211226	TYCO	Su/Pb	None	None	None	No	OK reflow, 260 °C, 60s.
	Plug	Leaded body	7221043	MOLEX G ØSTERVIG A/S	Su	None	None	Yes	Yes	Reject hot dip, 260 °C, 60s (2/2)
	Plug	SMD	7221283	MOLEX G ØSTERVIG A/S	Su/Pb	None	None	Yes	No	Reject reflow, 260 °C, 60s, (3/3)

The experience from lead-free sourcing at B&O so far shows that problem components include:

- Electrolytic capacitors
- Foil capacitors
- Opto-electrical components
- Relays

9.1.3 Main conclusions from the B&O case studies

- With two years left till RoHS implementations date, it is still difficult to get Leadfree / RoHS compatible components.
- It is still difficult to get component roadmaps from suppliers.
- Component reliability needs more focus.
- Still, a lot of new process problems are expected to show up, when changing to RoHS compliant process.

9.2 Nera Networks (N)

Nera Networks AS in Bergen, Norway, design and manufacture different types of products for the network telecommunication market. Main customers are companies like Ericsson, Nokia and Lucent technologies.

In the RoHS-directive such products have an exemption from the phase-out of lead in solder joints⁴. Their motivation for working on transmission to lead-free products summarizes as follows:

- Customer requirements
- Uncertainty when the exemption will end
- General transfer to lead-free components / materials
- Market advantages

In 2003, the company decided to:

- Comply with the RoHS directive, article 4 for all new product families
- Participate in the NoNE project
- Investigate impact for existing product families



Figure 9.12 Network infrastructure products from Nera.

⁴ RoHS exemption (Annex 1): Lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication.

9.2.1 Nera product cases

Three complex units were selected for the NoNE-case:

1. Converter microwave board
2. Modem board
3. IDU board

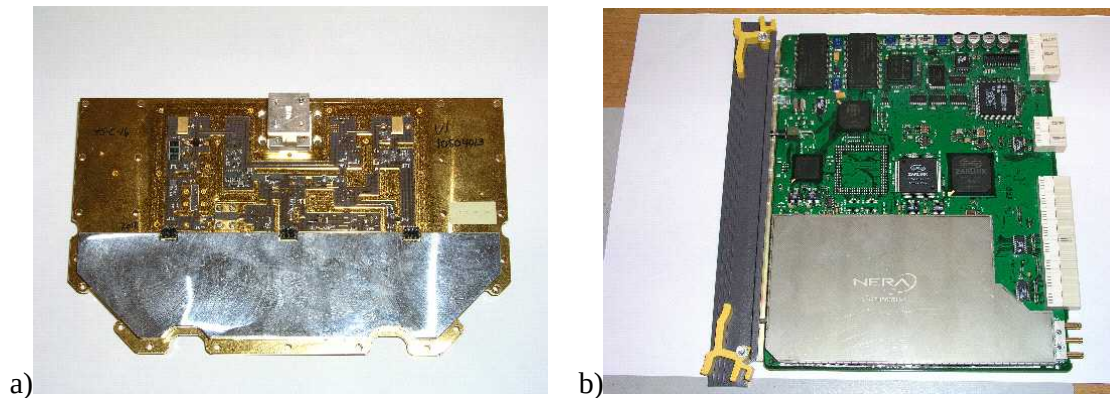


Figure 9.13 a) Converter unit (38 GHz). Board: PTFE, 0.254 mm, NiAu surface finish, base material: Al, 5 mm. b) Modem unit. FR4-board, 265 mm x 210 mm x 2.4 mm, HAL surface



Figure 9.14 IDU-board. FR4-board, 410 mm x 220 mm x 2.4 mm, NiAu surface

Lead-free soldering process

Conditions:

- Two boards with ENIG finish one with HASL
- 95% of the components were non lead-free
- Nitrogen used for reflow except Sikama
- Paste with no-clean flux

Lead-free solder paste:

- Paste A Sn95,5/Ag3,8/Cu0,7
- Paste B Sn96,5/Ag3/Cu0,5

3 different production sites were used, one for each board. Both internal and external manufactures were used.

Results

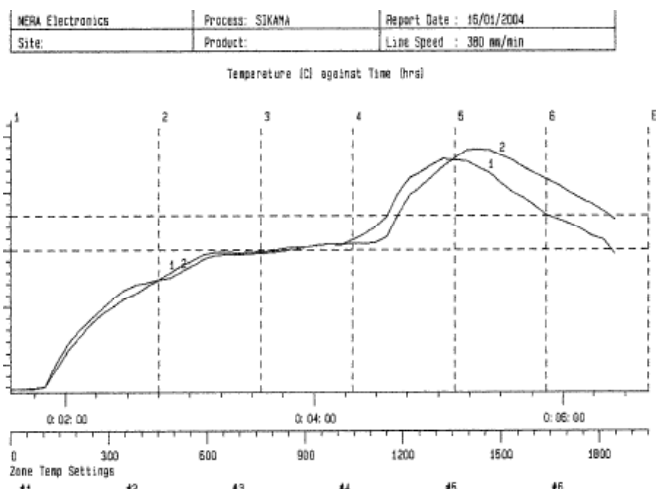


Figure 9.15 Soldering profile, Sikema (Falcon 8) reflow oven. Peak temperature: 239°C.

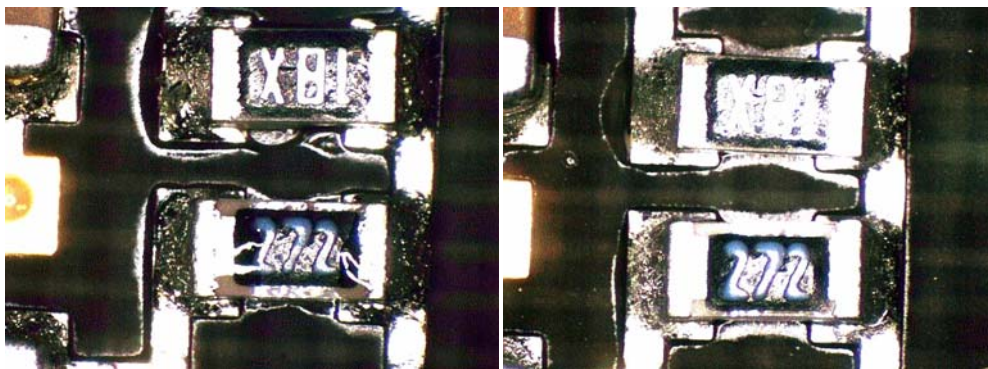


Figure 9.16 Solder paste A (left) and B. Dull and rough surface. Good wetting. Paste B slightly better than A; less flux residues and slightly smoother surface.

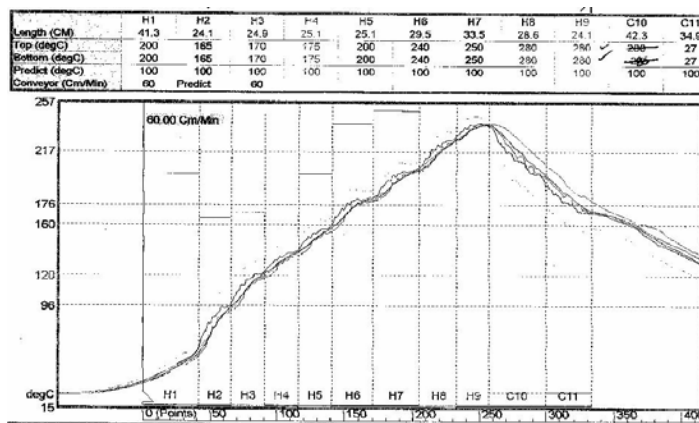


Figure 9.17 Modem unit. Solder profile, convection oven (Heller 1800EXL). Peak temperature: 246°C.

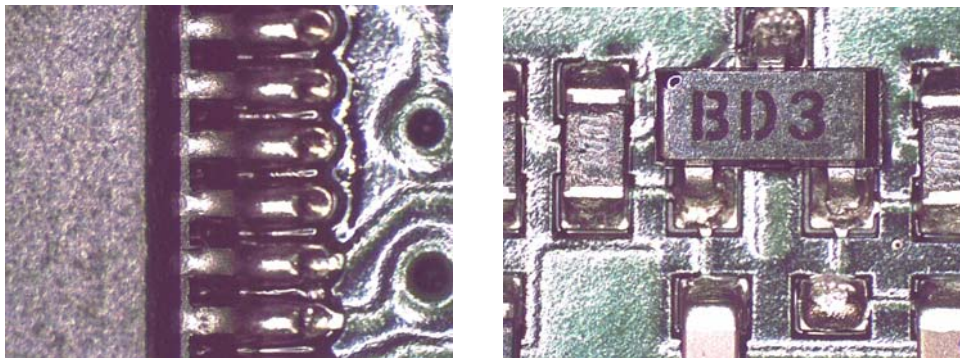


Figure 9.18 Modem unit. Fine pitch component (left) and chip components. Good wetting performance. Dull and rough surface.

Main observations from these tests are:

- Warpage in the center of the PCB flow direction observed after 2nd reflow. This resulted in improper screen box fixing and soldering.
- Good wetting of the components leads observed. Paste B solder is better.
- No solder ball/ beading is observed
- The colour of the screen box was tarnished due to high heat in the oven.
- Resistors network leads were tarnished

The recommendations is to use high Tg (170 degC) FR4 material for PCB fab. Concerning functional tests both boards failed at BST station immediately after power up. Therefore the boards cannot proceed to functional test. The fault was later located to a BGA component.

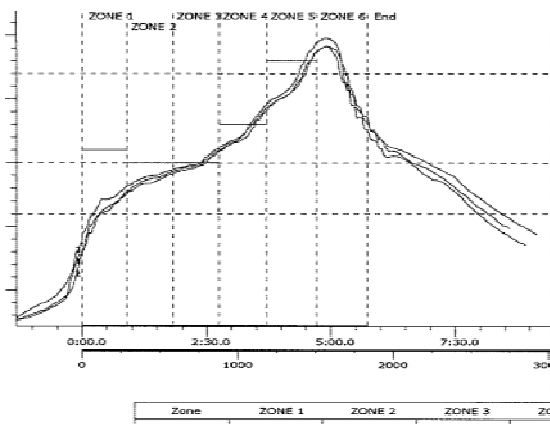


Figure 9.19 IDU unit. Solder profile, convection oven (Heller 1700EXL). Peak temperature: 250 °C.

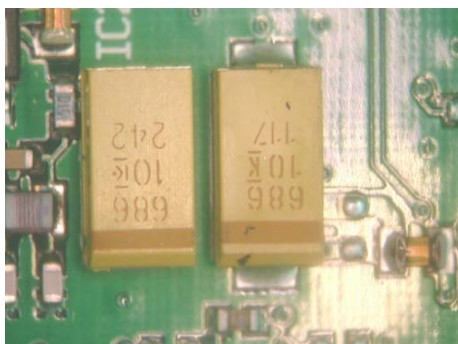


Figure 9.20 Components IDU unit. Greased label (left), Tantalum Capacitor slightly discolored (right)

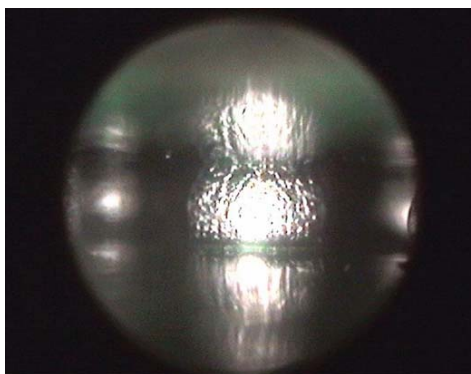
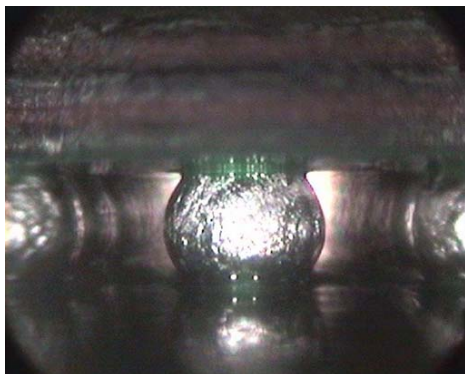


Figure 9.21 Components IDU unit. BGA soldering.

Observations for the IDU unit are that some minor workmanship deviations were observed, mainly for paste A. Some components were discoloured and a PCB warpage of 2mm was observed after the first reflow. In terms of functional test both boards failed initial Boundary Scan Test and the fault is located to 3 BGA's.

Failure analysis

A summary of the failure analysis performed for the Nera cases are found in Figures 9.22-9.24.

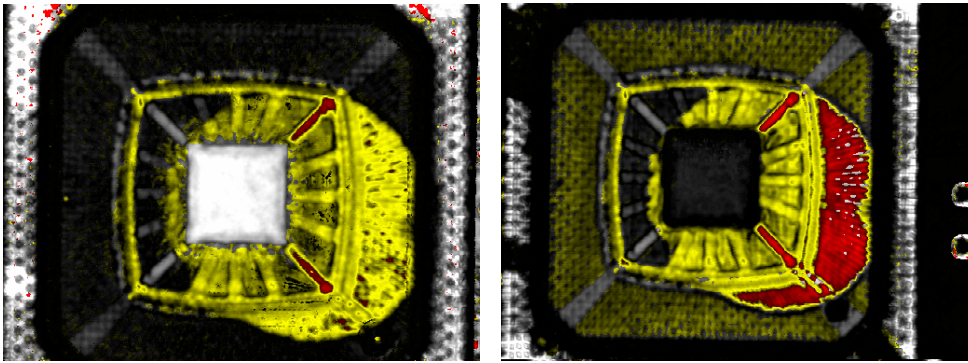


Figure 9.22 SAM picture of IC350, 87G40A-CNF41A, on the Modem Board showed a large delamination in the package/lead interface. No detected damage on the chip surface (left).

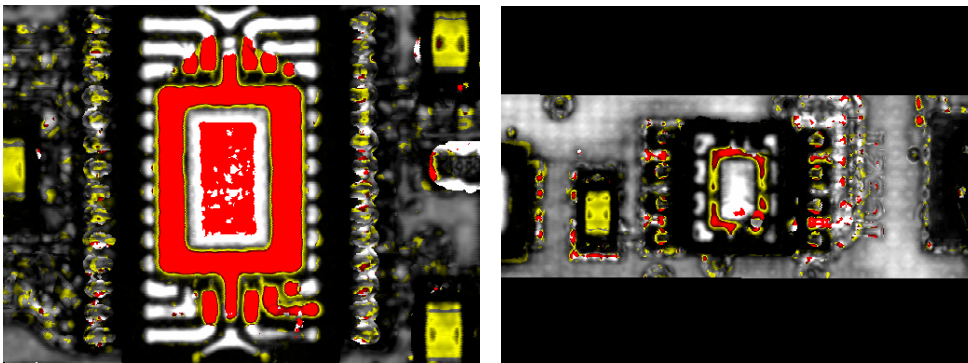


Figure 9.23 SAM pictures of IC210, 87G18-AD9051BRS60 (left) and IC921, 87G18-LM75CIM (right) revealed delamination in the die pad area. In IC210, delamination in the lead area was also detected. IC921 showed what could be beginning delamination damage in the chip surface area. No delaminations were found on the IDU boards.

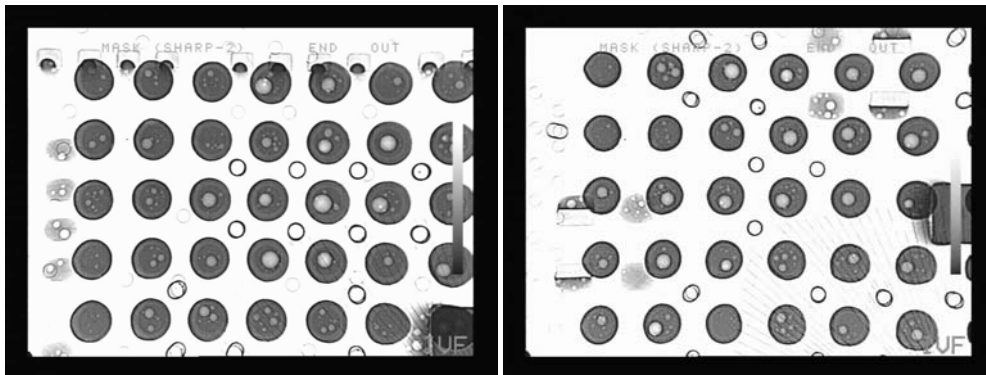


Figure 9.24 X-ray investigation revealed a large amount of voids in BGA bumps for both board types. In general, more voids were detected on the IDU boards than the modem boards. (The pictures are from IC350 and IC900, 87G33A-MPC850DEZT, on the Modem Board)

Conclusions and outlook

More tests to be done before the boards have been qualified include:

- Finish the analysis of the test boards
- Perform a HASS test of a lead-free and a non lead-free board
- Continue in house with evaluation of lead-free microwave boards including test
- Qualification of ASIC components

Re-qualification of components has revealed:

- Differences in component marking from one manufacturer to an other
- Change in HSL (1 to 3)
- Increasing # of LTB
- Some manufacturers are still on another planet....

Component compliance spec

*Table 9.2 Pb-free Process – Package Peak Reflow Temperatures
(Draft IPC/JEDEC J-std 020C)*

Package Thickness	Volume mm ³ < 350	Volume mm ³ 350 - 2000	Volume mm ³ > 2000
< 1,6 mm	260° +0/-5°C	260° +0/-5°C	260° +0/-5°C
1,6 – 2,5 mm	260° +0/-5°C	250° +0/-5°C	250° +0/-5°C
> 2,5 mm	250° +0/-5°C	250° +0/-5°C	245° +0/-5°C

Table 9.3 Classification reflow profiles (IPC/JEDEC J-STD-020B)

Profiles feature	Sn-Pb eutectic assembly	Pb-free assembly
Average ramp up rate	3°C/second max	3°C/second max
Preheat		
• Temperature min	100°C	100°C
• Temperature max	150°C	200°C
• Time	60-120 seconds	60-180 seconds
Time maintained above		
• Temperature	183°C	217°C
• Time	60-150 seconds	60-150 seco
Peak temperature	See table 1	See table 1
Time within 5°C of actual peak	15 seconds	15 seconds
Temperature		
Ramp down rate	6°C/second max	6°C/second max
Time 25°C to peak temperature	6 minutes max	8 minutes max

9.3 ABB Robotics (N)

ABB AS Robotics at Bryne south of Stavanger is the world leading manufacture of paint robots. Main customers are the car industry world wide. More information can be found at www.abb.com.



Figure 9.25 The robot range from ABB AS, Robotics, Bryne, Norway.



Figure 9.26 Paint robots from ABB AS, Robotics. The FlexLine system is a fully integrated paint system combining all advantages of cutting edge technologies.

9.3.1 ABB product case

The product case is a mixed technology board used for an ABB industry robot and is shown in Figure 9.27.

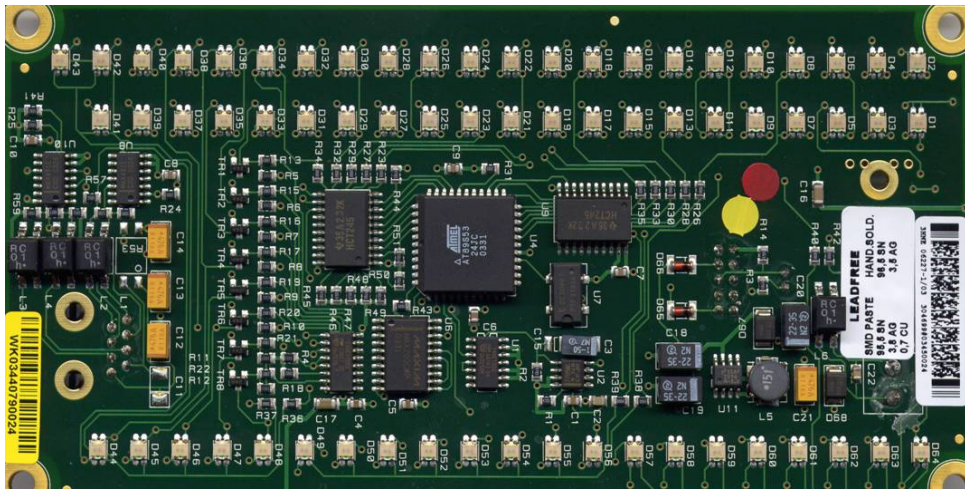


Figure 9.27 The ABB Robotics case board.

For the soldering tests performed at Kitron Arendal, the two alloys used are specified in Table 9.4.

Table 9.4 Solder alloys used for test production

Type	Manufacturer	Alloy	Melting point °C
Smd paste alloy	Indium	Sn95.5 Ag3.8 Cu0.7	217-218
Hand solder alloy	Kester	Sn96.5 Ag3.5	221

SAM-investigations of lead-free soldered PCBs

To qualify the lead free process for a specific product it is important to verify that the components have been assigned the correct JEDEC moisture sensitivity class. JEDEC 1, e.g., means that the components do not require drypack and therefore can be stored indefinitely in production environment and thereafter withstand reflow without delamination (pop-corning).

To this end, after the soldering processes the boards were investigated using Scanning Acoustic Microscopy (SAM) to reveal possible delaminations. A selection of pictures from the SAM investigation of lead-free soldered PCBs is shown below in Figures 9.28-9.31.

The SAM inspection revealed indications of delaminations in most of the investigated components. Some of the indicated delaminations were located in the wire bonding areas, which may be a cause of failure.



Figure 9.28 SAM image of QFP package showing indications (red areas) of delamination in the leadframe/encapsulant interface and in die pad/encapsulant interface areas.



Figure 9.29 SAM image of a SO-20 package showing indications (red areas) of delamination in the leadframe/encapsulant interface areas with possible openings from the outside environment into the stitch bond areas. In addition, there are indications of delaminations in the die pad/encapsulant interface areas.

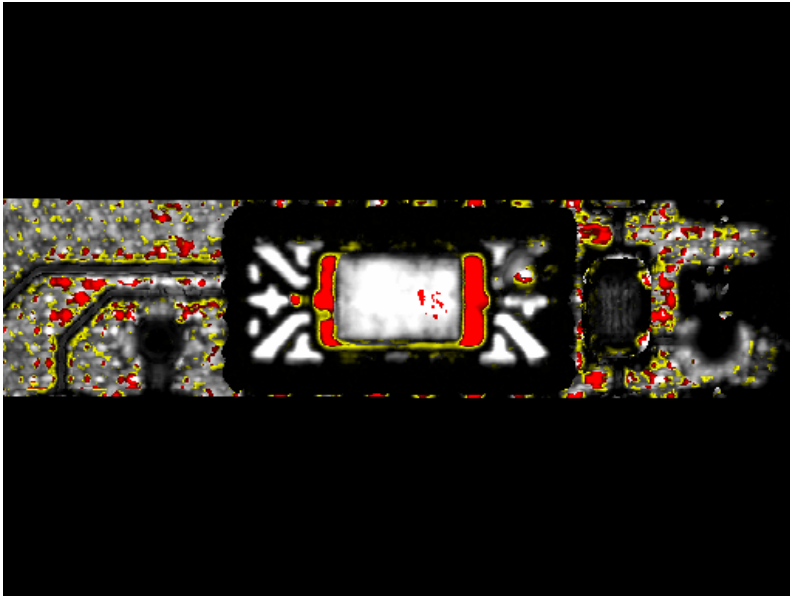


Figure 9.30 SAM image of a SO-14 package showing indications (red areas) of delamination in the leadframe/encapsulant interface and in the die pad/encapsulant interface areas.

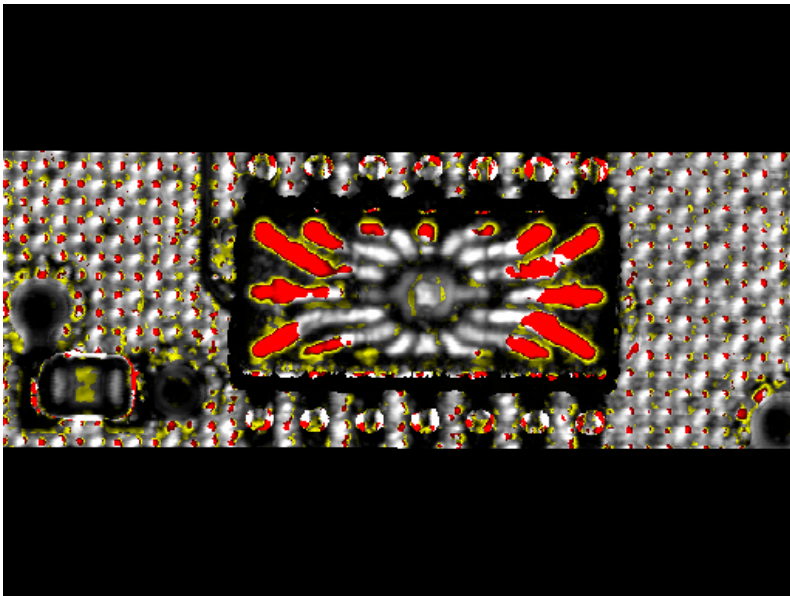


Figure 9.31 SAM image of a SO-14 package showing indications (red areas) of delamination in leadframe/encapsulant interface areas with possible openings from the outside environment into the stitch bond areas.

Investigations of delaminated components

In order to further investigate the cause of the delamination, possible remedies, and whether the delamination was present before reflow, a study of the effect of reflow on a selection of components was performed. The components were investigated both in as received condition and after reflow simulation using lead-free profile.

A selection of pictures from the Scanning Acoustic Microscope (SAM) investigation comparing components in “as received” condition to component in “after reflow” condition are shown in figure 9.32-9.34.

The SAM inspection revealed no indications of delaminations in any of the “as received” components as compared to “after reflow” components that all showed indications of delaminations. Some of the indicated delaminations were located in the wire bonding areas, which may be a cause of failure.

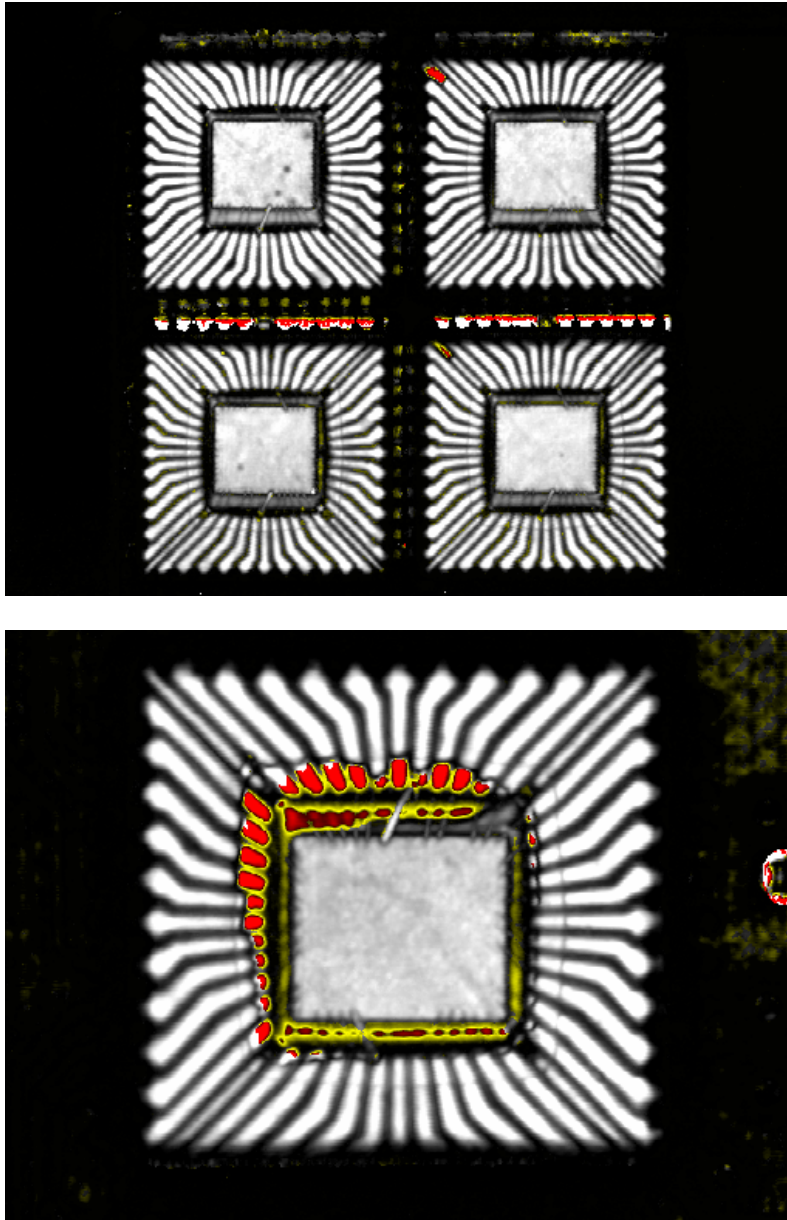


Figure 9.32 SAM images of the QFP packages in a “as received” condition (above) and in “after reflow” condition (below). The “as received” components show no indication of delamination as compared to the “after reflow” component.

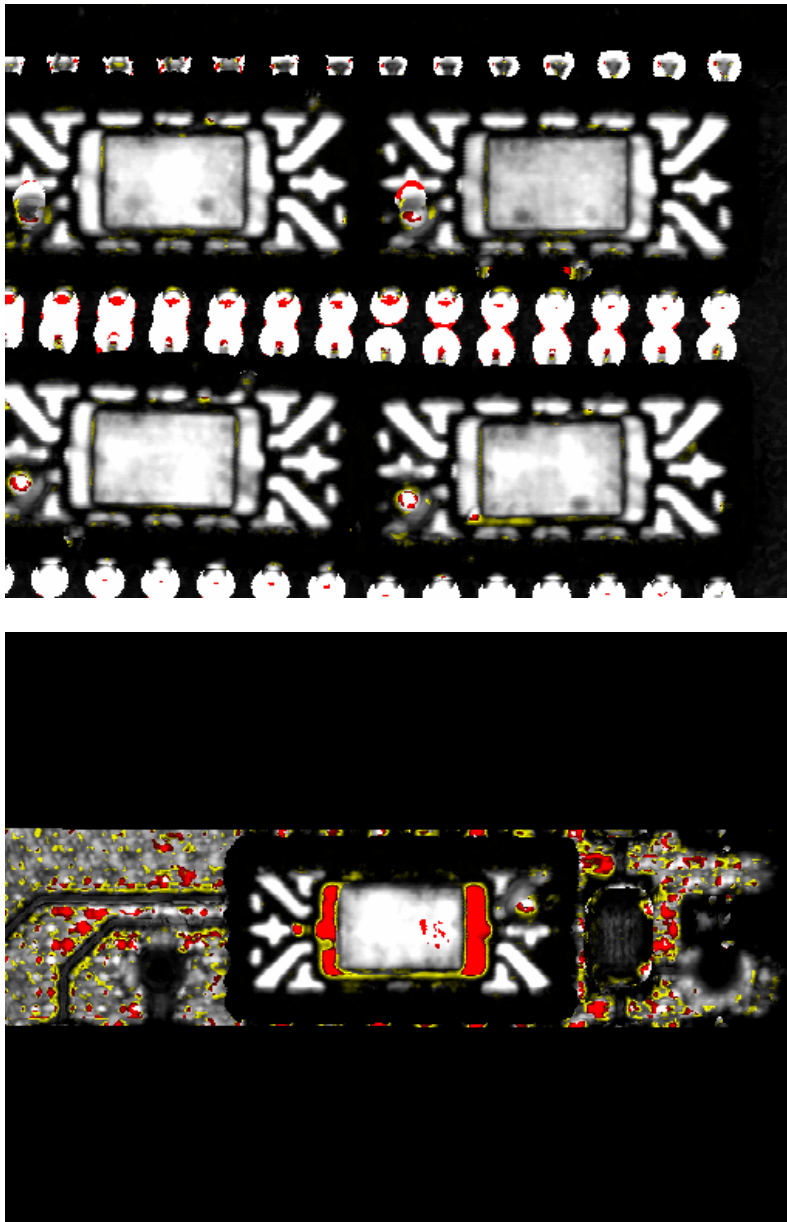


Figure 9.33 SAM images of the SO-14 packages in “as received” condition (above) and in “after reflow” condition (below). The “as received” components show no indication of delamination as compared to the “after reflow” component.

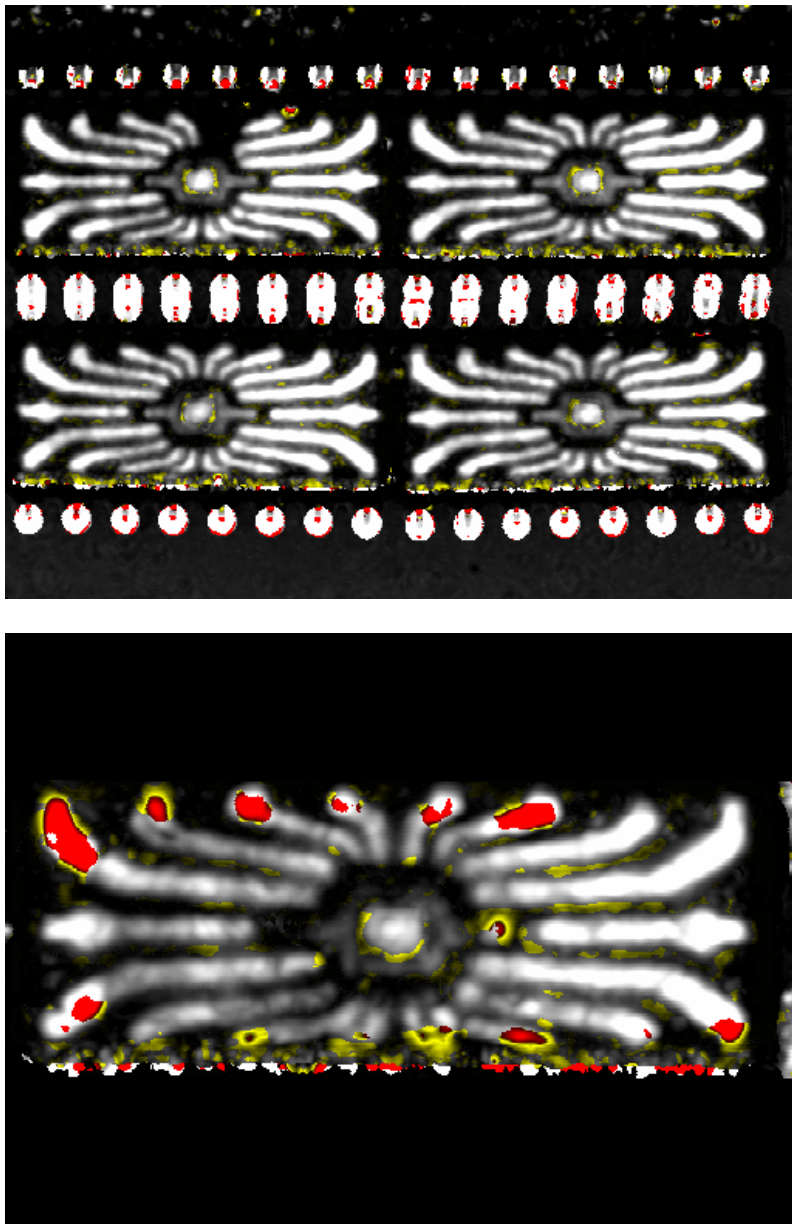


Figure 9.34 SAM image of SO-16 packages in “as received” condition (above) and in “after reflow” condition (below). The “as received” components show no indication of delamination as compared to the “after reflow” component.

Since all of the components showed delamination after reflow simulation, the JEDEC class assigned to the components were possibly incorrect. To go further in the investigation, the effect of pre-drying and time from breaking dry pack to reflow could be investigated to determine a safe handling procedure for the components prior to assembly and to verify that the correct JEDEC class is indeed given to the component by the manufacturer.

9.4 Tomra Systems (N)

Tomra designs and operates cost-effective systems that make it attractive for people to return used beverage containers for reuse or recycling. These systems consist of a wide range of products and services that complement the principal product group, reverse vending machines.

Reverse vending machines, or RVMs for short, are automated machines that utilize advanced technology to identify, sort, collect and process used beverage containers. In most cases, RVMs are used in markets that have deposits on beverage containers, offering an efficient and convenient method of identifying the deposit amount of each container returned and providing a refund to the customer.

Environmental commitment

In pursuing their mission of helping the world recycle, Tomra maintain a strong commitment to ensuring that their activities contribute positively to society and the environment. The intensive focus on quality and environmental best practices assures that the organization maintains the highest safety and quality approvals, including ISO 9001 and ISO 14001.

All of the more than five million metric tons of material collected through Tomra systems each year is brought back into productive use as new containers or as raw material for other products. This helps to reduce the volume of waste material sent to landfill, preserve valuable natural resources, save energy, reduce greenhouse gas emissions, increase public environmental awareness, and avoid the reduction of landscape value. This commitment, in combination with their own internal efforts to deliver positive social impact, is reflected by the fact that Tomra is listed on all major socially responsible investment (SRI) indexes.

In their environmental report from 2002, Tomra presented as the first Norwegian company a lead-free policy as an environmental goal for the next years:

“Tomra will introduce lead-free electronics in the products stepwise with the goal of have 100% lead-free products on the market in 2006/2007.”



Figure 9.35 Some of Tomras reverse vending machines for all types of beverage containers.

9.4.1 Tomra product case

The product case focused two mixed technology boards from one of Tomras reverse vending machines. They have been manufactured at Kitron Arendal. Two different board finishes have been chosen, HAL and chemical tin. After soldering, 50% of the boards have been tested in different environments (temperature, humidity). All boards were inspected and investigated by optical and x-ray measurements.

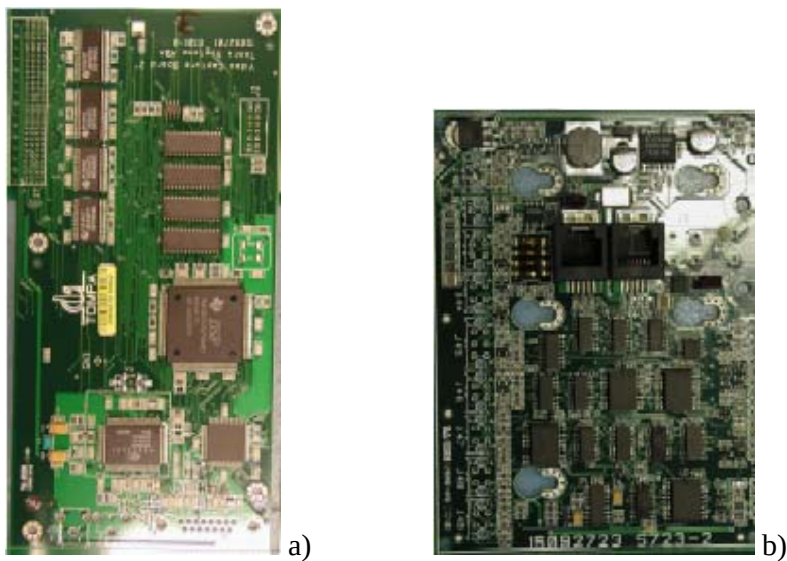


Figure 9.36 PCBs in the TOMRA case (C701 left & C723 right)

Process parameters

Table 9.5 Solder alloys used for test production

Type	Manufacturer	Alloy	Melting point °C
SMD paste alloy 1	Indium NC-SMQ230	Sn95.5 Ag3.8 Cu0.7	217
SMD paste alloy 2	Qualitek 889 (Delta)	Sn95.5 Ag3.8 Cu0.7	217-218
SMD paste alloy 3	Koki S3X58-M405L	Sn96.5 Ag3.0 Cu0.5	217-218
Wave soldering ⁵	STARLI	Sn95.5 Ag4.0 Cu0.5	217
Hand solder alloy	Koki S3X-51M	Sn90-95 Ag3-5 Cu0.5-1.0	217-218

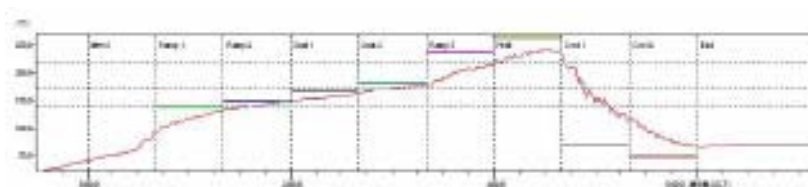


Figure 9.37 Soldering profile C701

⁵ Fluxes used: Alpha 215 (best results achieved) and Hi-Grade 3590T

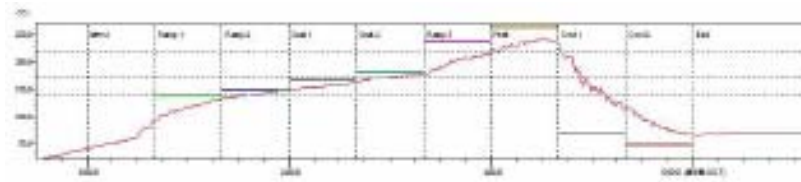


Figure 9.38 Soldering profile C723

Results

Pictures of the same components on the two boards (i.e. identical solder joints) are shown in figure 9.39-9.41 for board C701 and Figure 9.42-9.44 for board C723 for all three pastes used.

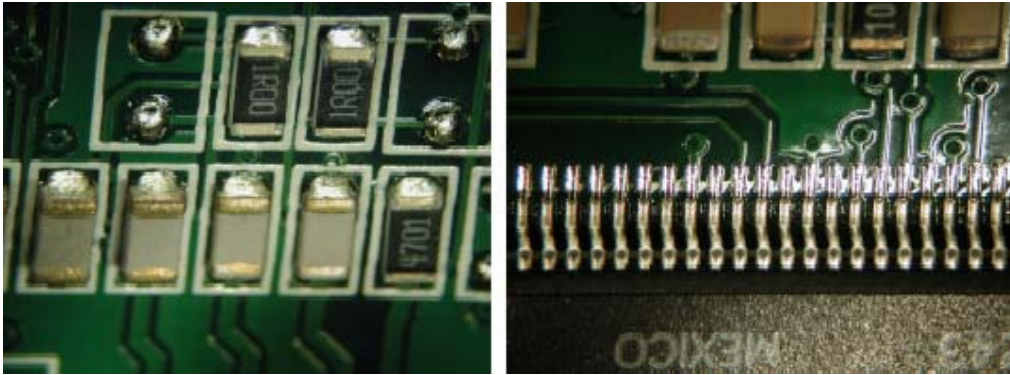


Figure 9.39 Board C701, Delta paste

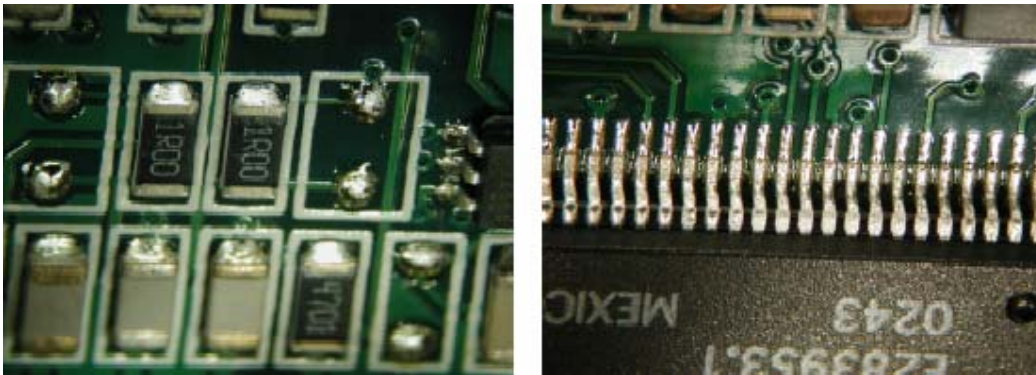


Figure 9.40 Board C701, Indium paste

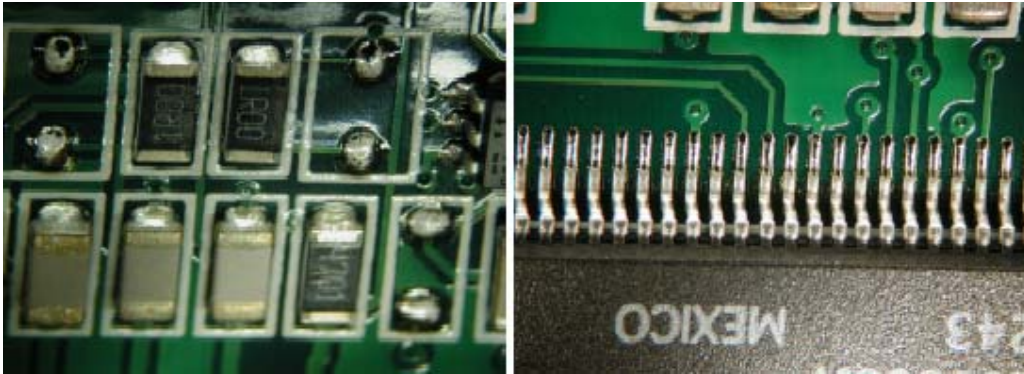


Figure 9.41 Board C701, Koki paste

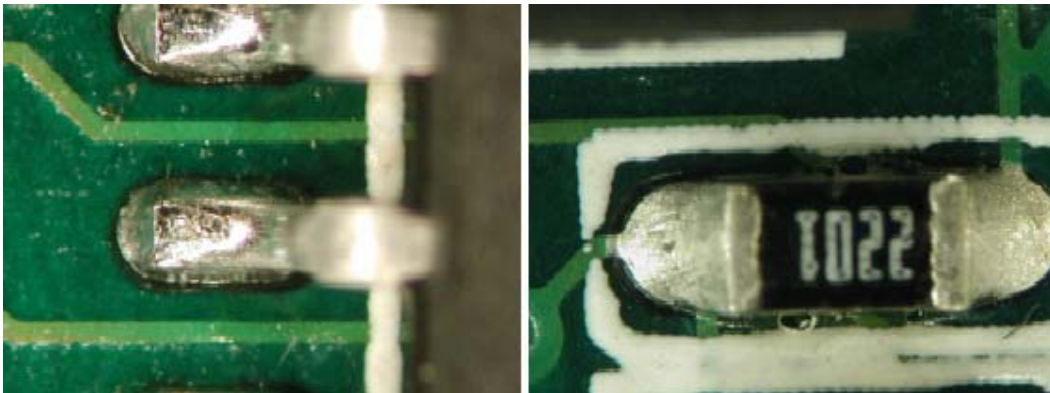


Figure 9.42 Board C723, Delta- paste

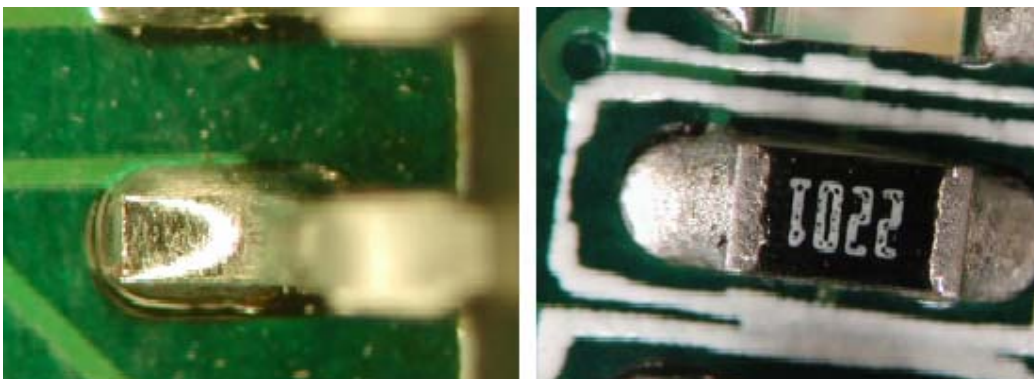


Figure 9.43 Board C723, Indium paste

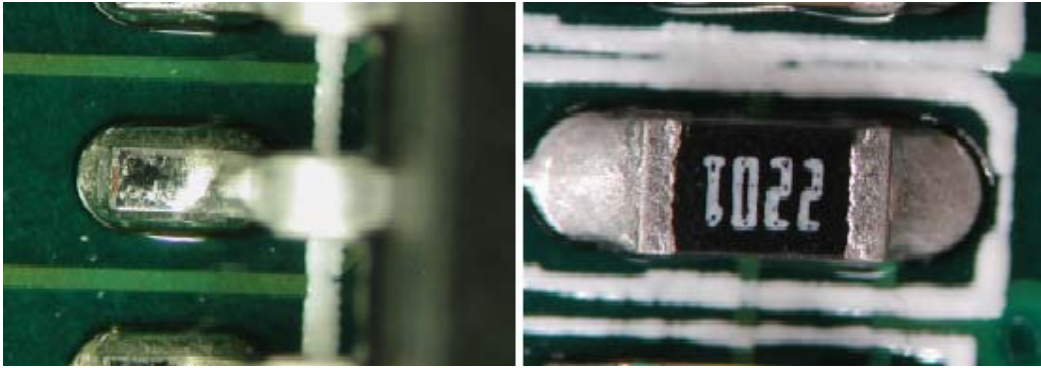


Figure 9.44 Board C723, Koki paste

Main conclusions

- Reflow process established. Smaller process window than for tin-lead solder. One of the paste gave a wider process window than the others.
- Wave soldering process established, without N₂. Two “standard” flux types tested with variable success.
- Hand soldering process established. Some difficulties for the operators. More heat and time needed. Solder joints looks different after soldering. More training needed.
- All boards tested OK in functional tests. Environmental tests reveal no degradation of boards so far.

Further work

Main topics to be worked with further in this case:

- *Soldering with other types of board finishes (Sn, i.e.)*
- *Wave soldering with nitrogen*
- *Flux systems in wave soldering*

9.5 Lövånger Elektronik (SE)

LEAB is one of the leading contract manufacturers of advanced electronics in Sweden. LEAB manufactures parts or entire products for our customers and deliver everything from surface mounted or hole mounted boards to complete products delivered directly to the customers customer.

About 3/4 of the revenue comes from complete products (box-build).

LEAB has offices in Lövånger and Stockholm and manufacturing in Lövånger and Estonia.

9.5.1 LEAB Case 1, Antenna for Balise

The antenna product case is part of a balise that has an expected lifetime of 30 years. This puts severe demands on the design and manufacturing. The antenna is shown in Figure 9.45 and the balise with the antenna cast at high temperature into the final structure is shown in Figure 9.46. The high casting temperature makes it necessary to use high melting solders to prevent reflow during the casting process.

The antenna is a 3.2 mm thick, two-layer board with OSP or Ag surface finish with very thick copper foil (70µm). On the board, coils, voltage transient protection components, and a few ceramic capacitors are mounted. The antenna is hand soldered today but wave soldering would be desirable to automate the soldering process. Some restrictions apply: To avoid cleaning the boards, L-class flux is desirable, since it is less aggressive.



Figure 9.45 Antenna for Balise shown in Figure 9.46



Figure 9.46 Balise before final assembly. Antenna is cast into the outer part of the structure.

Wave soldering tests in air

Wave soldering tests have been performed for the antenna shown in Figure 9.45. SnCu (SN100C) has been tested in air. The Table below summarises the tests so far.

Table 9.6 Wave soldering test production for antenna

Flux class	Flux used in test	Result
L0	Alpha 330	Ag better than OSP
	Qualitek 381	
	Qualitek 358	
	Heraeus Surf 11	Comparable to Alpha 330
M0	Alpha 310	
	Interflux 2009M	
H1	Qualitek 737N	

None of these fluxes give acceptable hole filling, however.

The best soldering result (IPC-A-610 class III) has been achieved with the following settings:

Table 9.7 Wave soldering parameters

Conveyor speed	0,5m/min
Pre heat	320-350°C
Bath temp	255-265°C
Solder time	9 s

For these settings, however, flux residues cannot be removed and components are damaged due to the long solder time.

Wave soldering tests in Nitrogen atmosphere

Wave soldering with SnCu (SN100C) has also been tested in Nitrogen gas (at HYTEK, Aalborg). The flux used is Circures Standard C 22 S – H 0.5% with a bath temperature of 270°C. The conveyor speeds tried were:

- 1,0 m/min
- 0,8 m/min
- 0,55m/min (still not OK)

The result is that only slightly better hole filling is achieved, but less dross is formed, and the number of defects is thereby decreased. The heating problem, however, is still not solved since component legs connected to upper copper layer still do not show acceptable filling. This is shown in Figures 9.47 a-c below. Acceptable soldering result is achieved only after extensive time in the wave while using aggressive flux. The flux residues, however, cannot be cleaned with these process conditions. For comparison, Figure 9.48 shows the result after hand soldering.

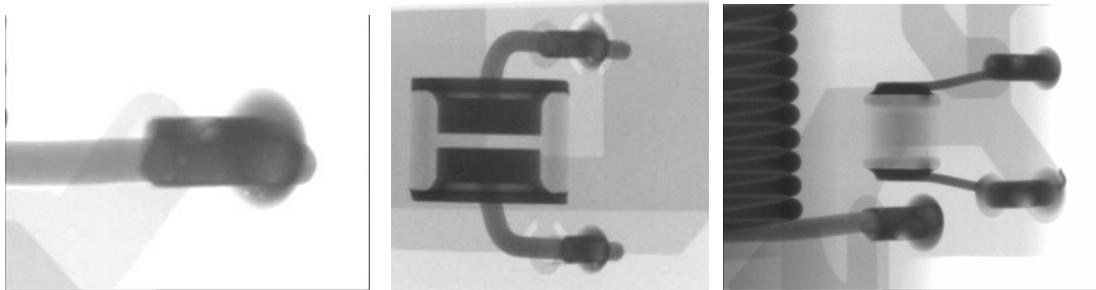


Figure 9.47 a, b, c Micro focus X-ray images showing insufficient hole filling after wave soldering in Nitrogen.

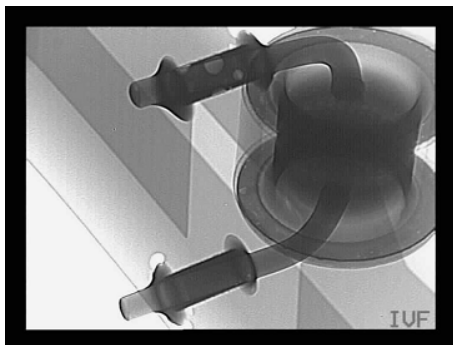


Figure 9.48 Micro focus X-ray picture showing good hole filling after hand soldering.

Optimization of design and process is ongoing and it is supported by the simulation work described in section 7.5.

Selective soldering tests

Conclusions after selective soldering tests are that 10 sec soldering time is needed which again leads to burning of flux and damage to components.

9.5.2 LEAB Case 2, Security board

Another customer project, with more traditional design and with both surface mounted and hole mounted components is the one shown in Figure 9.49.

The board is FR4 with a thickness of 1.6 mm. ENIG surface finish was used for these tests since lead-free HASL was not yet available.

Sourcing revealed that a few components, i.e. switch and connector strip, not yet are compatible with the higher reflow temperature. They will be available for lead-free process during Q1 2005.

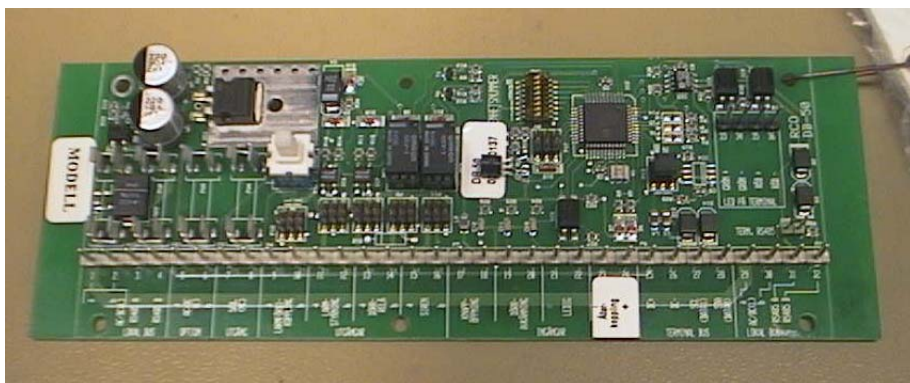


Figure 9.49 Printed circuit board assembly DB-50.

Wave soldering tests

Wave soldering tests have so far been performed with SN100C in Nitrogen atmosphere (at HYTEK, Aalborg). The result is that good wetting is observed visually. X-ray inspection reveals homogeneous joins without voids and with good wetting (see Figure 9.50).

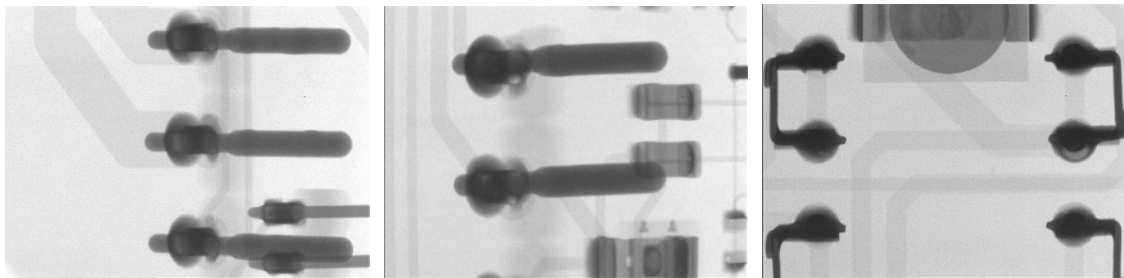


Figure 9.50 Micro focus X-ray pictures showing good soldering result after wave soldering in nitrogen.

Appendix 1 - Environmental aspects

The environmental impact of the various solders available to replace SnPb solder depends on the perspective taken. The reason lead is focused is its toxicity and tendency to bioaccumulate and, comparing SnPb37 to SnAg3Cu0,5, the leaded solder is considerably more toxic^{*}. If, on the other hand, we focus on more global and regional environmental problems, such as greenhouse effect and depletion, the lead-free solder could be considered a greater liability if you consider a simple LCA taking into account only the extraction of raw materials^{**}. If recycling is included the conclusions may change considerably.

Even if an LCA of a whole product system for an electronic product is performed, however, in a wider perspective the contribution of lead-free solders to global warming must be considered totally negligible, e.g. in comparison with the impact on global warming of the energy consumption of the product when in use. The real issue is the toxicity of lead and its replacements, the potential toxicity of fluxes, and to certain extent depletion of abiotic resources. This should really be the main focus when discussing the lead free replacement materials.

Nevertheless, the environmental impact of the replacement materials and the whole product must be considered. A phase out of lead will not solve all environmental problems for EE products, however, it will only give the product a better environmental performance with respect to toxicity. This is only part of the environmental profile of a product and it is important to focus also on other parameters e.g. recyclability, reusability, and life cycle environmental impact. The results from the Nordic GreenPack project, co-financed by the Nordic Industrial Fund, are now available at <http://www.greenpack.org>, and can be a starting point for those interested in environmental demands for EE products.

^{*} O. Deubzer, H. Hamano, T. Suga, University of Tokyo, Japan, H. Griesse, Fraunhofer IZM, Berlin, Germany, *Lead-free soldering – toxicity, energy and resource consumption* The Institute of Electrical and Electronics Engineers (IEEE), 2001.

^{**} Johan Widheden, IVF, *Comparative, simplified life-cycle analysis of leaded and lead-free solders*. Report for the Swedish lead-free project. AIS-18.