The effect of rework on brittle fractures in lead-free solder joints

The growth of intermetallic compounds during rework and its effects

Degree Project of 30 credit points
Master of Science and Engineering, Mechanical Engineering

Date/Term: 09-12-15 / HT - 08
Supervisor: Christer Burman
Examiner: Jens Bengström
Abstract
Saab Microwave Systems is a supplier of radar systems. The circuit boards operating in their radars have components which solder joints contains lead. However, the EU directives RoHS and WEEE are causing SMW to prepare for a transition to lead free solder joints. The objective of this thesis is to gain a deeper knowledge of lead free solder joints.

Brittle fractures in solder joints are a type of failure that might increase in the transition to lead free solder joints. The brittle fractures are induced by the creation of intermetallic phases which are formed during soldering. The amount and composition of intermetallics affects the mechanical strength of the joint. An intermetallic layer is thickened during heat exposure as during soldering, thermal aging and rework.

The focus of this thesis was to investigate how repairs affect the brittleness of the lead free solder joints, and thereby how the intermetallic layers change depending on chemical composition, design and reflow cycle. Two types of components and two solder materials (SnPb and SAC305) were studied.

To study the mechanical properties a shear testing device was used. This is a way to measure the reliability of the joint when subjected to mechanical shock. The intermetallic layers were examined in a Scanning Electron Microscope and the fracture surfaces were examined in an Optical Microscope, a Scanning Electron Microscope and Stereomicroscope. The heat spread over the board during rework was examined by soldering thermocouples to the board and plotting the values of time and temperature.

The results showed that the rework process did not have any significant impact on the intermetallic growth. The adjacent and distant components were not damaged during rework. A lead free rework process can therefore be performed successfully at Saab Microwave Systems. The intermetallic layer formed at the interface between a lead free solder and a nickel finish grew faster than an intermetallic layer formed between a leaded solder and a nickel surface. The presence of nickel could therefore have a more negative effect on the intermetallic growth rate for the lead free material compared to the leaded.
1 Table of content

Abstract.......................................................................................................................... 1
1 Table of content............................................................................................................ 2
2 Introduction.................................................................................................................... 5
  2.1 Company description ......................................................................................... 5
  2.2 Background ....................................................................................................... 5
  2.3 Purpose ............................................................................................................. 6
  2.4 Limitations ....................................................................................................... 6
3 Theory.......................................................................................................................... 8
  3.1 Printed Circuit Boards ....................................................................................... 8
  3.1.1 Surface finish ............................................................................................... 10
  3.2 Components .................................................................................................... 12
  3.2.1 Ball Grid Array, BGA ................................................................................ 12
  3.2.2 Quad Flat Non-Leaded (QFN) ..................................................................... 14
  3.3 Soldering .......................................................................................................... 15
  3.3.1 Vapour phase oven ....................................................................................... 17
  3.3.2 Materials used for soldering ........................................................................ 18
  3.3.3 Temperature profiles .................................................................................... 19
  3.4 Rework ............................................................................................................. 20
  3.4.1 Rework temperature profiles for lead free solders ...................................... 21
  3.4.2 Rework of lead-free solder ......................................................................... 21
  3.4.3 Rework at Saab – the process ..................................................................... 22
  3.5 Intermetallic compound (IMC) ....................................................................... 26
  3.5.1 Phase diagrams ........................................................................................... 27
  3.5.2 Leaded material and IMC ............................................................................ 29
  3.5.3 Lead-free material and IMC ........................................................................ 31
  3.5.4 The growth rate of the intermetallic layer when exposed to rework, reflow or aging ........................................................................................................ 32
  3.6 Other problems to consider in a transition to lead-free ................................. 36
  3.6.1 Kirkendall voids ......................................................................................... 36
  3.6.2 Whiskers .................................................................................................... 36
  3.6.3 Pad Cratering .............................................................................................. 37
4 Materials and Methods.............................................................................................. 38
  4.1 Test plan .......................................................................................................... 38
  4.1.1 The test vehicle ............................................................................................ 38
  4.1.2 Processes .................................................................................................... 42
  4.1.3 Methods for analysing results .................................................................... 45
5 Results....................................................................................................................... 52
15.1.2 Leaded rework

16 Appendix E

16.1 Heat spread over board – Lead free (Note: B=C and C=B)

16.2 Heat spread over board – Leaded (Note: B=C and C=B)

17 Appendix F

17.1 Temp.profile Solder paste LFM48 TM-HP Sn-Ag-Cu

18 Appendix G

18.1 SEM analysis

18.1.1 Leaded - PCB

18.1.2 Lead free – PCB spot 1

18.1.3 Lead free – PCB

18.1.4 Lead free – PCB spot 2
2 Introduction

2.1 Company description
Saab Microwave Systems, SMW is a supplier of radar systems. Their products profile includes airborne, ground based and naval radar systems. The company was owned by Ericsson until 2006 when it was sold to Saab and took the name Saab Microwave Systems. The company has 50 years worth of experience in radar development and delivers radars all over the world. They have products operating in 30 countries.

A collection of their products are: ERIEYE – air and sea, ARTHUR – Weapon location radar for protection and firing control, GIRAFFE AMB – Ground based multi-role surveillance radar and HARD – Air defense search and acquisition.

2.2 Background
According to the EU directives RoHS and WEEE all electronic and electrical products were supposed to be lead-free by the 1st of July 2006. The directives did not, and still do not, comprise military products and thereby not the products of Saab Microwave Systems. However, the access to products containing lead is rapidly decreasing because of the fact that electronic component suppliers are included in the RoHS directive, and this is causing SMW to prepare for a transition from leaded to lead-free products.

The products of SMW that contains lead are particularly the solder joints of the components that are mounted on the circuit boards which are operating in their radars.

The transition will affect many steps of the production line and it will require changes in the soldering process when mounting the components. It might also affect the reliability of the components. Therefore, a deeper understanding of how to handle these materials is needed.

Brittle fracture in solder joints is a type of failure that might increase in the transition to lead-free [1, 4]. The brittle fractures are induced by the creation of intermetallic phases. An intermetallic layer is created during soldering and it is present in both leaded and lead-free solders. However, the problem with brittle fractures in the intermetallic phase is more often seen in lead-free products.
This is because the lead free solder joints sometimes have a thicker intermetallic layer than the leaded solder joints and the lead free intermetallic layers are not as well known as the leaded. The amount and composition of intermetallics affects the mechanical strength of the joint [1, 3].

Because of the new and unexplored concerns, the transition to lead-free solders will require many studies and tests in advance. Saab Microwave’s products are used in high reliability applications and in order to be sure that the products will fulfill their requirements they want to be as prepared as possible for a transition.

EQS is a research network which aim is to develop tools and provide knowledge to participating companies in order to achieve a more efficient product development of electronic hardware. SMW is one of the participating members of EQS.

EQS first project will be “Brittle fractures in solder joints” and this thesis will be a part of that study. The objective of that project and this thesis is to gain a deeper knowledge of lead-free solder joints and how they behave.

The focus of this thesis will be how repairs affect the brittleness of the lead free solder joints, and thereby how the intermetallic layers, which are formed during soldering, change depending on chemical compositions, design and reflow cycles. The results for the lead free solder joints are to be compared with the results from the leaded solder joints.

2.3 Purpose
The purpose of this thesis is to gain more knowledge of how reparations effects the brittleness of solder joints and what the consequences will be if SMW will have to start using lead free materials in their processes.

2.4 Limitations
The thesis work is limited to 20 weeks and therefore the parameters included in the experimental part had to be somewhat restricted. The components, solder materials and surface finishes that were of the most interest for the company, were therefore studied.
To study how the brittleness of the solders were influenced by rework and chemical compositions in the solder joint, a shear testing device was used. This is a way to measure the reliability of the joint when subjected to mechanical shock (high strain rates).
3 Theory

3.1 Printed Circuit Boards

Printed Circuit Boards (PCB) consist of a laminate, principally built up by two layers; a base material and a copper foil. The copper is used because of its high electrical and thermal conductivity, and besides from that it is easy to solder. The base material varies depending on which application the circuit board is used in, it is supposed to be electrically isolating, have a low absorption, be dimension stable when exposed to heat and have a low thermal conductivity. The glass transition temperature, decomposition temperature and coefficient of thermal expansion are important properties when choosing the base material (read more in appendix A), especially when dealing with lead-free processes due to fact that a lead free process requires higher soldering temperatures. Prepreg (Pre-impregnated material) is a resin matrix system that is used in most circuit boards. A cross-section of the prepreg can be seen in picture 2. The reinforcement can be glass fibers or ceramics and the matrix can consist of epoxy, teflon, polyimide or cyanatester. The most common prepreg is FR-4, which is a glass fiber epoxy. The laminate consists of an epoxy which is strengthened with a glass fiber. In figure 2 the fibers can be seen in x and y direction. FR stands for flame retardant, which is a part of the epoxy structure.

![Prepreg diagram](image)

*Fig. 1 shows a cross-section of a six layer PCB [52]*

A PCB can be built up by several layers and they are named after how many layers of copper that they consist of. For example: a 6 layer PCB consist of 6 copper layers. The two outer layers, as well as the four inner layers are made out of copper, see figure 1.
The circuit board has a pattern or a footprint on the topside of the board. The footprints show where the components are going to be placed during the mounting process, see figure 3. The visible pattern is copper with a surface treatment and it acts as a connector. For the surface mounted components the pattern is exposed as a soldering surface, so that components can be soldered directly onto the surface.

To protect the visible copper a solder mask is applied to the exposed areas of the circuit boards. The solder mask is supposed to prevent the copper from corroding and is also meant to isolate the electrical circuit. On some areas it is more appropriate to protect the copper by providing it with a surface finish instead of a solder paste, for example on places where a surface mounted component is going to be attached [5].
3.1.1 Surface finish

When selecting a surface finish it is important make the choice based on what the application is meant to be, for example which type of component that is going to be soldered to the surface. There are many types of surface finishes each with its limitations as well as advantages.

Hot Air Soldering, HASL, is the most commonly used soldering process, and it is used for both leaded and lead-free alloys, though it is more common for leaded ones. Other surface finishes that are more popular in lead-free processes are electroless nickel based finishes (ENIG, ENIGEG, ENEPIG), electrolytic nickel, finishes on copper (Immersion Silver, IAg and Immersion Tin, ISn) and mixed finishes (OSP, ENIG, DIG). A more detailed description of the most common surface finishes are as follows.

**Hot Air Solder Leveling, HASL**

HASL stands for Hot Air Solder Leveling and it is a way of solder processing a surface finish. Before the hot air solder leveling process is performed the copper surfaces is cleaned so that the oxidation layers as well as other dirt is removed, after that the flux is applied. The flux is a liquid that removes the remaining oxide and protects the copper from further oxidation. The circuit board is then lowered in a bath of solder. The temperature of the solder bath is different depending on which alloy is used. As the circuit board is elevated from the bath hot air is blown on the board. Since the hot air is blown with such a high pressure on the board, the coating of solder is flattened and the abundance of solder is removed. The remaining flux is removed before the process is finished [5].

The positive sides to HASL are that the surface finish has a great soldering ability, good shelf life and it is not an expensive treatment. The downsides to the process are that the circuit board is exposed to a thermal shock when it is lowered into the bath of over 200ºC which can make the surface uneven [5].
**Electroless Nickel Immersion Gold, ENIG**

Electroless nickel/immersion gold is the name of the surface finish commonly known as ENIG. ENIG is a chemical surface treatment with a mixture of the materials nickel and gold.

This surface treatment requires a cleaning of the copper surface before the actual process starts. After that, a catalyst material is applied to the copper surface of the circuit board, and then the board is subjected in a nickel bath so that the catalyst can react with the nickel. After a layer of nickel has formed on the surface a gold coating is applied. The gold is also applied to prevent the copper from reacting with its environment and the nickel which in turn prevents the copper from diffusing into the gold [5].

ENIG can withstand high temperature ranges, has good corrosion resistance, good wetting and good solderability. The downsides to this surface treatment are that it is expensive and if the gold layer is too thick it can easily cause the solder joint to be brittle. Brittle fractures on assemblies soldered using tin-lead solders has mainly been reported when they are soldered to copper surfaces with a ENIG surface finish [1].

A problem that exits with ENIG is black pad failures. The black pad occurs during the immersion gold step, due to corrosion of the nickel layer. The black pads can separate the solder joint from the nickel surface and cause it to open. The failure is called black pad due to the fact that a blackened appearance is seen on the pad surface when the phenomenon appears [1, 5, 46].

An ENIG surface finish contains phosphorus. During both immersion gold plating and soldering nickel is dissolved from the surface, which results in an enrichment in phosphorus and formation of Ni₃P. The black pad effect is caused by too extensive dissolution of nickel during immersion gold plating and the formation of a thick layer of Ni₃P [1].
Electrolytic Nickel, Ni/Au
Deposition of electrolytic plating is based on the discharge of metal ions from a cathode in a metal salt solution. Metal ions in the solution are reduced to the surface to be plated, which is charged with an electric current. The plated surface acts as the cathode and the bath acts as an anode, together they act as a sink for the electronic current. When the metal containing salt solution receives electrons from the copper pads (the current source) the metal is plated on the copper pads [6].

The difference between the electrolytic and the electroless process is that the electrolytic process uses an external electric current source to drive the plating reaction whereas in the electroless process the electrons are provided by a reducing agent [6].

Electrolytic nickel does not contain phosphorus and therefore are the solder joints soldered to electrolytic nickel less prone to brittle fractures. Electrolytic nickel is usually coated with a thick layer of gold and if this layer is too thick it can cause embrittlement of the solder joint [6, 1].

3.2 Components
Surface mounting means that the solder joints of the components are soldered directly to the soldering surfaces of the circuit board, also known as the pads. There are several component families available on the market. Some of them are mentioned below.

3.2.1 Ball Grid Array, BGA
A BGA is a component that has balls of solder stuck to the bottom of the package. The main task of a BGA is to transfer the electrical signals between the printed circuit board and the connecting package, and this is done through the solder balls. There are different types of BGA and they have different designs, but there are some general similarities between them. All of them are intended for surface mounted applications and the connectors are always balls of metals. The component is situated on a circuit board that has a footprint which matches the pattern of the components solder balls.
Fig. 4 shows the bottom side of two different types of BGA components [66, 67]

The pattern of the BGA can vary, the balls can have different dimensions and the pitch (center-to-center between two balls) can be different. Figure 4a), 4b), 5a) show an example of a BGA pattern and figure 5b) shows an example of a BGA pitch. There are several different combinations of patterns and pitches on the market, but usually the pitch for a BGA is about 0.8-1.27 mm. The number of balls on a BGA component can vary, but most commonly they range from 50-500. However, at SMW more than 1000 are also normal.

Fig. 5 shows a) An example of a BGA pattern b) The pitch of this BGA is 1 mm

Since the balls are situated at the bottom of the component it is hard to make sure that the soldering process was performed correctly. Therefore an X-ray is used to inspect that the work was properly preformed. What determines whether the soldering process is good or not is if the X-ray pictures shows uneven/misshaped or circular solder balls, see figure 6. An uneven and misshaped BGA indicates that the soldering process was unsuccessful and circular shaped BGA means that the soldering process was successful.
14

Fig. 6 shows a) uneven/misshaped BGA means that the soldering process was unsuccessful [68] b) Circular shaped BGA means that the soldering process was successful [69]

BGA components are frequently used at SMW and other electronic companies and many experimental reports have been performed to evaluate how a transition to lead free will affect the mechanical strength of them. The risk of brittle fractures in lead free solder joints is reported to be especially a problem for BGA components [4].

3.2.2 Quad Flat Non-Leaded (QFN)
A Quad Flat, Non-Leaded package is a leadless package with land pads that are situated on the edges of each side of the components on the bottom of the package. In the middle of land pads there is one exposed die pad that supplies the package with thermal integrity – a cooling pad, see figure 7. The land pad is primarily what separates the QFN from other packages. Other components most often have “legs” which sticks out of the package body and forms, for example, a J-shape or a ball. The land pattern on QFN resides on the bottom of the package body, so it is not as exposed as most component legs, see figure 8.

Fig. 7 shows the land pattern of a typical QFN, the larger pad in the middle is the cooling pad [70]
The QFN package is primarily used in applications that require great thermal and electrical performance. An advantage with the QFN is that it has a low standoff height off the pads (the height of the solder joints) so it is appropriate to used where a reduced size and weight is preferable. A disadvantage with QFN is also the low standoff height of the legs because it makes the handling of the component more difficult. For example, it makes the component hard to clean after soldering.

![QFN Package Image]

Fig. 8 shows the cross section of QFN [71].

There are two general types of QFN packages, Air-Cavity QFN and Plastic-Moulded QFN. The Air-Cavity type is built up by two parts; a plastic compound and a copper lead frame. The Plastic-Moulded type is fully encapsulated and has no cavity in the package. It has three parts which it consists of; a plastic-moulded body, a copper lead frame and a lid of plastic or ceramics. The air cavity type can withstand higher levels of electrical frequency then the plastic moulded one.

The rework process of a QFN component is not very different from the BGA rework processes. After rework, reflow or repair the QFN can be inspected both visually and through X-ray techniques.

### 3.3 Soldering

Soldering is when two metal pieces are joined together by melting a solder metal into the joint. The solder metal has a relatively low melting point compared to the two metals that are going to be joined. A successful soldering process often means good wetting. A good wetting means that the solder spreads well over the surface.

To achieve a good soldering or wetting the surface at which the solder joint is going to be attached to, needs to be perfectly clean. An oxidized dirty copper surface has bad wetting and is thereby difficult to solder. If the surface is clean, the flux can be applied.
Flux is used to improve the solderability of the intended component and to prevent oxidation during the soldering process. Flux also acts as a wetting substance in the soldering process. The wetting makes it easier to join the metal to the solder joint and reduces the surface tension. The flux is applied in a so called solder paste. Solder paste is a homogenous mixture of flux; viscosity modifiers and a metal alloy. The paste has the same function as the flux: it improves the solderability. The paste is applied on the pads of the circuit boards.

The solder paste alloy may contain lead but there are also lead-free solder paste alloys available. The spread of the solder paste depends on the solder paste alloy, for example a leaded paste usually has better wetting than the lead-free pastes.

The solder paste is applied to the circuit boards using a stencil, specially designed for the circuit board intended. The stencil boards have etched openings, and through them the solder reaches the circuit board. The stencils are often made of stainless steel. After the solder paste is applied to the board the components are placed on the solder paste. A machine picks up the components with a claw or vacuum device from tubes which keep them sealed, and place them where the paste already is applied. The positioning is controlled by laser or cameras. For each type of circuit board the surface mounting machine needs to be individually programmed due to the fact that the design and placement of components are differs from board to board.

After the components are placed the soldering process can take place. The temperature of the soldering process varies a lot depending on what material is going to be soldered. Each material and component has its own temperature profile. (Read more about the temperature profiles in section 2.3.3). During the soldering bath the solder paste melts and connects the pad with the solder joint.

There are different ways of soldering. Of course the work can be done manually by hand tools. However, this technique is never used for mass-production, just for repair or rework. The most common processes used in electronic assemblies are:
• **Reflow soldering** – This type of soldering is used for surface mounted components. A carefully-controlled oven is used to join the surface mounted components to the boards. Different reflow soldering can be performed with a vapour phase oven or convection oven.

• **Wave soldering** – Waves of molten solder are used to attach the metal components to the circuit board. The method is used for both through-hole printed circuit assemblies and surface mounted assemblies.

After the soldering the boards are cleaned and inspected.

### 3.3.1 Vapour phase oven

At SMW a vapour phase oven is used when soldering. A vapour phase oven is a soldering equipment and a type of reflow soldering. The equipment uses vapour to heat up the printed circuit boards by using a liquid that has a boiling point that is appropriate for the board that is supposed to be reflowed. The heat arises from the thermal energy which is emitted by the phase change of the heat transfer liquid condensing on the PCB.

There are several advantages of the vapour phase oven. First of all, it is oxygen free, which improves the solderability. Secondly, there will never be overheating of the boards due to the fact that the boiling point of the vapour medium is limiting the maximum temperature of the boards. Thirdly, the vapour medium has a better thermal transfer property which makes the heat transfer over the boards more even. Due to these advantages, the vapour phase oven is the most recommended equipment in the lead-free soldering industry. Since lead-free processing involves processing PCB at higher temperature it increases the risk of exposing the boards to higher stress, and therefore it is extra important with good heat transfer and limited maximum temperature [60, 61].

There are two vapour phase ovens at Saab, one for lead-free soldering and one for leaded soldering. The lead-free oven uses a vapour medium that vaporizes at 240ºC. The oven where the leaded components are soldered has a vapour medium that vaporizes at 215 ºC.
3.3.2 Materials used for soldering

3.3.2.1 Lead free materials used for soldering

SAC alloys
For the electronics industry the tin/silver/copper (SAC) alloys are the most popular lead free materials. The silver content is typically between 3.0 – 4.0 w% and the copper content is between 0.5 – 0.9 w%. Two of the alloys in the SAC family have been studied a bit more carefully, SAC 405 and SAC 305. Some favour SAC 405 (Sn3.8Ag0.8Cu) and others favour SAC 305 (Sn3.0Ag0.5Cu). As might be expected SAC305 is less expensive due to its lower silver content, but according to tests SAC305 does not have as high reliability in high application areas as SAC405 [11]. However, at this time it is difficult to draw any general conclusions as to which material is most suitable for a solder joint. The SAC305 alloy has a melting range temperature of about 217ºC [9, 11].

As the silver content is reduced, the melting temperature increases. For example, the melting temperature of SAC105 (Sn1.0Ag0.5Cu) is around 227ºC compared to SAC305 which has a melting temperature of 217ºC. To elevate the melting temperature is not preferable in a lead-free process due to the fact that lead-free solder already requires a high melting point.

SnCuNi
SnCuNi is a new popular lead-free alternative in soldering. The material has a copper content of 0.7% and a low Ni content which is added to increase the fluidity of the material at soldering temperatures. The SnCuNi solder is a good alternative to the SAC family due to its lower price. SnCuNi is patented by Nihon Superior Co Ltd and a more common name for the product is SN100C.

Compared to SAC alloys, SN100C is still a relative new material in soldering, which means it has not been studied as carefully as SAC. The SAC family is also more preferred as a lead-free alternative compared to SN100C due to its lower melting point. The melting point of SnCu is about 227ºC [9, 11].
3.3.3 Temperature profiles
The temperature profile of a soldering process is established by taking several parameters under consideration; the chemical composition of all of the materials involved during the process, the soldering process available and the dimensions and design of the boards.

To simplify, there are three basic steps involved when establishing a temperature profile; pre-heat, reflow and cool. Each step has a certain time limit and a temperature limit which can not be exceeded. Figure 9 shows a typical temperature profile.

A temperature profile can be developed in different ways and usually there is much effort put into developing them. To prepare for a transition to lead-free a lot of research has already been put in on developing specific lead-free temperature profiles.

When designing a temperature profile thermocouples are placed on key locations of a component and on the board in order to investigate how the temperature varies across the board and the over a component. Knowing how the temperature will spread across the components and the circuit boards it is easier to develop a suitable temperature profile [15].

Important to consider while developing the temperature profiles is to not expose the components and board to thermal shock but to ramp up, not staying at the higher temperature levels for too long and damage the components and have an even temperature over the components and the boards.
The thickness of the circuit board also affects the temperature profile quite a lot. A thicker board usually means more copper in the material and this affects the heat transfer of the circuit boards due to coppers material properties. Since copper transfer heat well, a thick copper means that the heat can transfer quicker in the board. This is something that also needs to be taken under consideration when developing a temperature profile.

The time above liquidus and \( \Delta T \) (maximum temperature during soldering – alloy melting point) affects the thickness of intermetallic layers which influences the mechanical properties of the solder joints. The longer time the solder is in a liquidus phase and the higher the temperatures it is exposed for, the thicker is the intermetallic layer [24, 39, 55]. This is also important to consider when developing a temperature profile.

### 3.4 Rework

Rework or repair of a component is done when a component fails or a defect is found. Some defects are possible to repair but many components that have defects are removed and replaced with a new component (reworked). The rework process is done with different care depending on what kind of application the solder joint is supposed to be used in. In high reliability applications the rework needs to be carefully performed while in other applications the rework can be done more hastily. Rework and repair are essential practices for high cost electronics like the ones SMW are producing. Generally, a repair process is done according to the following steps:

1. Establish a thermal profile suitable for the component used
2. Remove the defective component
3. Clean and prepare for the new component
4. Place new solder paste or flux on the circuit board
5. Reflow
6. Clean
7. Inspect
The components are situated close to each other making the rework process harmful for surrounding components. The problem can escalate in a transition to lead-free products due to the higher temperatures involved with the process [56].

3.4.1 Rework temperature profiles for lead free solders

The melting temperature for a lead-free solder is about 40°C higher than for a solder containing lead and this will affect all steps in the temperature profile. Table 1 gives an idea of how a transition from lead to lead-free can influence the time and temperature limits.

The higher temperatures involved will have many negative effects. For example, the higher temperatures can make the circuit boards expand and this can cause the inner layers of the board to crack. The higher temperatures may also have an effect on the equipment and the components. This is one out of many things that has to be considered when developing a rework temperature profile for lead-free components.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Leaded Temperature (°C)</th>
<th>Time (sec)</th>
<th>Lead-free Temperature (°C)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-heat</td>
<td>100-120</td>
<td>60-90</td>
<td>130-140</td>
<td>100</td>
</tr>
<tr>
<td>Soak</td>
<td>160-170</td>
<td>90</td>
<td>140-170</td>
<td>90</td>
</tr>
<tr>
<td>Ramp</td>
<td>NONE</td>
<td>-</td>
<td>170-225</td>
<td>100</td>
</tr>
<tr>
<td>Reflow</td>
<td>Max 220</td>
<td>60</td>
<td>225-235</td>
<td>15-30</td>
</tr>
<tr>
<td>Cool</td>
<td>60</td>
<td>30-60</td>
<td>60</td>
<td>30-60</td>
</tr>
</tbody>
</table>

As seen in Table 1, the lead-free process needs to ramp up slower, and when the peak temperature is reached it needs to be quickly cooled down again (reflow leaded: 60 sec and reflow lead-free: 15-30 sec). The ramp that is present in the lead-free process is required so that the packages will not be damaged due to thermal shock [56].

3.4.2 Rework of lead-free solder

A transition from leaded products to lead-free would mean concerns for the personnel dealing with the rework and repairs of the products. Rework of a product of this type already requires high skills and precision of the operator, and this will not ease in a transition to lead-free.
Some of the things that will affect the rework and the soldering process in a transition to lead-free solders are:

- The temperature profile is different for the lead-free components; the soldering temperature is higher, the pre-heat temperature is higher and the total reflow profile range over a longer period of time [56, 57].
- Due to the higher temperatures involved with lead-free soldering it is important that the equipment and the other materials involved can handle the higher temperatures [57].
- Adjacent components are exposed to a higher temperature when reworking a board. This means that it is extra important to protect surrounding components so they will not take damage [2].
- The lead-free pastes does not wet or spread as well as the leaded ones, due to their higher surface tension. This may require a design change in the stencils used for rework, so that they fit the land patterns better [62].
- Lead-free materials are more sensitive to moisture than leaded ones. Therefore it is important that the parts are stored in dry boxes or sealed in a bag when not being reworked [57].

**3.4.3 Rework at Saab – the process**

At Saab Microwave Systems, there is a department that works with repair and rework of components that for example has bad wetting or does not pass the electrical test. A typical defect can be that the soldering of a joint was not good enough. The products at Saab are considered to be used in an application that requires high reliability, and therefore reparation and rework is done with extreme accuracy.

**Example – Rework on a BGA component**

**Removal of defective component**

When repairing a BGA component at Saab Microwave Systems, the first thing that is done is that the circuit board is dried. This is done in an oven of 100ºC for 24 hours.

The second step of the process is to make sure that surrounding components will not be in the way or be damaged during the repair process. Sometimes there are resistors situated very close to the BGA components, and these are removed before the soldering
process starts. These resistors are relatively easy to place back after the insertion of the new BGA. If there are components that are situated close to the defective component these are not taken away, instead they are protected during the exposure to heat.

Fig. 10 The equipment used when performing reflow.

When removing the defective component a machine called “LEICA MS5, SR SIERRA” is used. The machine has nozzles that are used to first transfer heat and then remove the defect component. There are several nozzle sizes available, so a nozzle that has the same dimensions as the defective BGA component is used. Each circuit board has a specific temperature profile that is followed during heating of the component. The temperature profile has different steps of heating up the material and the profile is designed after the solder material dissolving temperature. Before the heating of the component starts the surrounding components are protected with aluminum foil. The operator also specifies what type of component that is going to be removed and which type of circuit board it is attached too.

First, the circuit board is heated from underneath (see figure 10) and then the nozzle is lowered down over the component. After the temperature profile is carried out, heat is transferred through the nozzle (see figure 11) and when the solder balls have melted, the component is lifted up and removed.
Unfortunately, after the component is removed there are often remaining pieces of the BGA bumps left on the circuit boards, which need to be cleaned away. The cleaning tool used for this application is a so called solder-wick. A solder-wick is a thread made of oxygen free copper, which is treated with a solder flux. It is used as a tool to remove solder from solder joints. To remove the solder, the wick is pressed onto the solder joint and heated up to the tip of the soldering iron, where the remaining pieces of the BGA components are. As the flux melts to the wick and the solder reaches its melting point, the solder “wicks” the clean copper thread. The copper and the solder react due to the heat and the solder is thereby removed from the circuit board. An illustrative picture of the solder wick method is presented below in figure 12.

**Insertion of a new component**

Once the cleaning of the parts are completed it is time to assemble the new component to the circuit board. The first step is to apply the solder paste on the board using a metal stencil. The stencil is placed where the old component was situated and the holes of the
stencil are aligned with the holes where the removed BGA bumps used to sit. When the stencil is placed the paste is applied using a small scraper, see figure 13.

![Stencil and scraper](image)

*Fig. 13 A stencil and scraper is used when applying solder paste to the board where the components are attached [72].*

The next step is to place the new component on the circuit board. The operator specifies what type of component which is to be assembled and at which type of circuit board it is going to be attached to. Naturally, it is important to make sure that the new component is placed at the exact place that it should be placed.

When the component is placed the soldering process begins. The process starts by pre-heating the circuit board from underneath up to a specific temperature which depends on the temperature profile. The nozzle is then lowered, surrounding components are protected and the top heater starts working.

A rework of a BGA component at SMW takes about 6-8 h. It is the cleaning of the remaining pieces of the BGA that takes the longest time. The careful cleaning is necessary to guarantee the high reliability of the final product. At a company that produces products which do not require as high reliability as at SMW a rework process can take 1-5 hours.

After the soldering process is finished it is important to make sure that the process was performed correctly. This is done both visually and with the help of an x-ray, by looking at the shape of the solder balls.
### 3.5 Intermetallic compound (IMC)

Crystalline metals can contain many different types of phases. Usually there is foreign elements dissolved into the matrix which can cause distortion in the metal but the basic crystalline structure is still the same. However, sometimes they can introduce a completely new crystalline phase, one which has a structure which is different from the parent material. These phases are called intermetallic compounds. Picture 14 shows where on the solder the intermetallic layer is formed. The formation of intermetallics occurs in three stages; dissolution, chemical reaction and solidification.

The solid metallisation dissolves into the liquid solder and the rate and temperature depend on the metal. First, the base metal exists only at the solid-liquid interface and then the liquid supersaturates into the metal. Sometimes two layers of the IMC are formed. One is thin and rich of the base material and the other one is thicker and more irregular. The properties of intermetallic compounds can be very different from the compound materials.

Every time a solder joint is attached to a metallic surface by a soldering, an intermetallic layer is formed at the solder/surface finish interface. Depending on the amount of the layer it can act as a good foothold for the components. At low levels the layer has a strengthening effect on the joint but at higher levels the layer makes the joint hard and brittle [13, 15, 39].

![SnPb IMC](image)

**Fig. 14** The intermetallic layer is formed in the solder/surface finish interface. Picture a) shows the intermetallic layer between a SnPb BGA solder ball that is attached to a copper pad. The photo is taken using a Scanning Electron Microscopy. Picture b) shows an overview of the cross section of a BGA solder joint that is soldered to a copper pad with a nickel surface finish.

Due to embrittlement caused by high levels of IMC the solder joint can easily fracture when exposed to mechanical loading. Different types of typical mechanical loading that
a solder joint are likely to be exposed to are: rapid change in temperatures, bending of circuit boards, mechanical shock (dropping circuit boards) and vibrations.

Most brittle fractures of solder joints occur during handling directly after the soldering process. The reason as to why the solder joint is extra sensitive at this time is because after soldering the residual stress is very high in the solder joints, as time passes the stress is reduced due to the creep in the solder. Along with that, the risk of brittle fracture is reduced [4].

The intermetallic layer also affects the electronic properties. The IMC has poor electrical properties and disturbs the flow of the electrons. This can delay signals in electrical products [34].

The thickness of the intermetallic layer increases with the increasing number of soldering cycles and if it reaches a temperature over 60ºC further growth of the IMC is induced [55]. This means that during a reflow process the IMC could thicken.

The chemical compositions of the pads and thereby the morphology of the IMC are affecting the degree of stiffness of the joint as well as the risk of brittle fractures. The most commonly used surfaces finishes have either a copper base or a nickel base (HASL- Copper, ENIG – Nickel).

**3.5.1 Phase diagrams**
There are some typical intermetallics that are well known in the electronic industry. There are SnCu, SnNi and SnAg intermetallics. All of them have several different intermetallic phase diagrams as seen in figure 15, which will have to be taken under consideration when soldering.
Cu is the base metal when soldering in the electronic industry. Two important intermetallics can be formed during soldering with Cu and Sn and that is; \( \text{Cu}_3\text{Sn} \) and \( \text{Cu}_6\text{Sn}_5 \). Sometimes, Ni is used as a barrier between Sn and Cu so that the reaction rate will be slower. When soldering to Ni surfaces, \( \text{Ni}_3\text{Sn}_4 \) is the most common intermetallic observed but \( \text{Ni}_3\text{Sn} \) and \( \text{Ni}_3\text{Sn}_2 \) are also stable under 260°C. Ag is another common metallisation in lead free electronics. Ag diffuses rapidly into the liquid solder. There is only one intermetallic that is of interest when soldering with Ag, and that is \( \text{Ag}_3\text{Sn} \) [6, 58].

The intermetallics are often more complex that the ones listed above, for example a SAC solder contains Ag, Sn and Cu and during dissolution process elements can react and form even ternary intermetallics. For each system there can be many different intermetallics and the brittleness for the intermetallics can vary greatly [58].

Fig. 15 show the phase diagram of CuSn, NiSn and AgSn [6, 58]
3.5.2 Leaded material and IMC

Copper surface
When a tin-lead solder is soldered together with a copper surface the bottom layer of the solder surface is quickly supersaturated with the copper. The compositions of the intermetallics that are formed are Cu₆Sn₅. After a normal soldering process these intermetallics are rounded scallop-shaped, see figure 16. The structure of the IMC is formed when the solder solidifies. The thickness of the IMC will vary over the surface of the component, but are usually between 0.5 – 2 µm after mounting [1]. There can also be a layer of Cu₃Sn at the interface between the Cu₆Sn₅ and the copper, but after a soldering process this layer is usually so thin that it is difficult to detect. If the solder joint is aged over a temperature of 60ºC the intermetallics grow and if it exceeds a thickness of 5-7 µm the second phase of the IMC (Cu₃Sn) can usually be detected [1].

During aging the intermetallics grow and the structure of the layer goes from rounded to elongated scallop-shaped. The higher the temperatures the joint is exposed to the faster the growth of the intermetallic layer [40, 44].

As the intermetallic formed does not contain any lead, the growth of the compounds may cause a formation of a layer with a lead-rich phase in between the intermetallic layer and the solder [1].

Nickel surfaces
Nickel has a slow dissolution rate in a molten solder and therefore it is often used as a barrier between copper and tin to limit the dissolution [1,5, 6]. Because of the low dissolution most of the dissolved nickel is found in the IMC layer.

Two common nickel finishes are Electroless nickel and Electrolytic nickel. Electroless nickel contains phosphorus whereas electrolytic nickel does not. To preserve the solderability of these finishes, they are often coated with a corrosion resistant metal like palladium or gold. For example an area array component with electrolytic nickel are usually coated with 0.5-1.5µm electrolytic gold whereas electroless nickel is usually coated with 0.02-0.2µm [1]. As the soldering process starts the gold dissolves quickly in the solder.
The IMC layers on nickel finishes are much more complex than on copper surfaces. The composition and structure of the IMC and thereby properties of nickel finishes can vary. Usually there is only one phase of intermetallics formed after soldering to a nickel surface, but after aging two phases may be seen. The composition of the IMC of the electroless nickel is Ni$_3$Sn$_4$ and for the electrolytic nickel there are two phases Ni$_3$Sn$_2$ and Ni$_3$Sn$_4$. The Ni$_3$Sn$_2$ is the phase closest to the nickel finish [1].

Some studies say that the IMC growth is faster on electrolytic nickel than on electroless nickel in a SnPb solder during aging but some reports have contradictory results. This can be due to the P content in electroless nickel. An electroless finish with less than 7-8% P has a nanocrystalline structure and a finish with more than 7-8% P has an amorphous structure. The microstructure may have an impact of the grow rate of the IMC and this may explain the contradictory results [1].

As mentioned previously, a nickel surface is often coated with gold to preserve the solderability. The effect of that is that the gold dissolves in the solder. If the concentration exceeds 0.3-0.4 % AuSn$_4$ may be formed. AuSn$_4$ looks like needle-like crystals. If the gold exceeds 3-5% gold the solder joint can become brittle due to the formation of AuSn$_4$ compounds. This is usually not a problem for finishes with electroless gold finishes due to the fact that it is usually so thin. However, it can be a problem for electrolytic gold finishes – if the solder volume is small. For a BGA component with electrolytic gold finish on the solder lands it should not be a problem because of the large solder volume, the gold content will stay below 3% [1].

However, studies have shown that when a solder joint that has a nickel surface with a gold coating that is aged, another type of gold embrittlement can occur, despite the fact that the gold content is lower than 3%. When the gold is redistributed in the solder during aging it can form an Au$_X$Ni$_{1-X}$Sn$_4$ on top of the Ni$_3$Sn$_4$ layer. The formation of the Au$_X$Ni$_{1-X}$Sn$_4$ can be prevented by increasing the nickel dissolved in the solder or by adding 0.5% Cu to the SnPb solder [1].
3.5.3 Lead-free material and IMC

Copper
The chemical composition of the IMC formed at the interface between lead free solders and copper surfaces are the same as the intermetallics formed on SnPb/Cu solders. The main phase is Cu₆Sn₅ but sometimes there is also a thin layer of Cu₃Sn present.

The reports on the thickness of the IMC in lead free processes are contradictory. Usually the IMC layer formed on lead free solders are said to be thicker than on SnPb but when soldering with SnAg solders it can also be thinner [1]. It has also been reported that the thickness of the IMC depends strongly on the solder volume [1].

On lead free copper surfaces the intermetallic layer’s morphology also changes with reflow time, from rounded scallop shaped to elongated scallop or rod shape. At the same time the thickness increases. This is illustrated in figure 16 below [44].

![Figure 16](image)

Fig. 16 The IM thickness of a Sn - 0.7Cu/Cu solder increases with reflow time. The solder is reflowed at 225°C from a) 1s b) 1 min c) 10 min and d) 30 min. During reflow time the structure of the IMC goes from rounded scallop to elongated [44]

The composition and morphology of the IMC layers are formed on copper or copper that is coated with a surface coating (HASL, OSP, Immersion tin and immersion silver) are basically the same. A copper surface that is coated with immersion silver can have a layer of Ag₃Sn needles just above the Cu₆Sn₅ layer [1].
**Nickel surfaces**

The intermetallic that is formed when soldering a Sn-Ag solder to nickel is usually the same as for a Sn-Pb solder that is soldered to nickel, \( \text{Ni}_3\text{Sn}_4 \). \( \text{Ni}_3\text{Sn} \) and \( \text{Ni}_3\text{Sn}_2 \) have also been seen when soldering above 250ºC [1]. The difference between leaded and lead free is that when soldering lead free with nickel surfaces, large amounts of \( \text{Ni}_3\text{Sn}_4 \) are frequently reported. When soldering to SnAg solders, spalling of the IMC layer may occur. Spalling is when IMC layer is separated from the interface. The problem with spalling has been seen with electroless nickel [1].

The intermetallics formed on a lead free solder depends on the copper content of the solder. If the copper content is less than 0.4%, \( \text{Ni}_3\text{Sn}_4 \) will be formed, and some of the nickel will be substituted with Cu. If the copper content is higher than about 0.6%, \( (\text{Cu},\text{Ni})_6\text{Sn}_5 \) will form. If the copper content is between 0.4-0.6 % a dual layer will be formed. The dual layer consist of \( (\text{Ni},\text{Cu})_3\text{Sn}_4 \) and \( (\text{Cu},\text{Ni})_6\text{Sn}_5 \) where the first one mentioned is closest to the nickel surface [1].

**3.5.4 The growth rate of the intermetallic layer when exposed to rework, reflow or aging**

The intermetallic layer in a solder joint thickens during its service life. Therefore it is important to limit the growth of the IMC, so it will not be harmful to the long-time reliability of the solder. At room temperature an intermetallic layer of 1 µm is formed in one year. As the thickness increases the growth rate decreases quickly. Generally the growth rate of the intermetallic layers should not have any severe effect when exposed to temperatures below 100ºC [55].

During both reflow and rework the temperature is well above 100ºC. A component, and thereby its joints, often goes through multiple reflow cycles due to the fact that various components are mounted in different levels on the circuit boards. Sometimes the boards have to be refloved up to three times. During each time the thickness of the intermetallic layer grows. The growth rate depends on the design of the component, the chemical composition of the solder and also the time and temperature above liquidus. The longer time the solder is in a liquidus phase and the higher the temperatures it is exposed to, the thicker the intermetallic layer is created [24, 39, and 55].
3.5.4.1 Leaded and copper

After mounting the thickness of the intermetallic layers on SnPb solders are usually between 0.5-2.5 µm. The large variation is probably due to approximations when measuring uneven layers, as well as the difference in processes and temperature profiles [55].

It shall be noted that the growth behaviour when aging is different from the growth rate during reflow. During reflow the IMC thickness is uneven regardless the thickness of the IMC. However, during aging the intermetallic layer gets more even as the IMC thickness increases.

As mentioned the intermetallic thickens during its service life and for SnPb solders the growth rate depends on the degree of Sn in the solder, the more Sn the faster the growth rate. Figure 17 shows how a Cu₆Sn₅ intermetallic layer between a SnPb resistor and a copper surface thickens at a temperature of 230ºC. Figure 18 shows how a Cu₆Sn₅ intermetallic layer between a SnPb solder and a copper surface thickens depending on time and temperatures [55].
3.5.4.2 Leaded and Nickel

When soldering to Nickel the composition of the IMC is much more complicated as when soldering to copper, both for leaded and lead free solders. The growth rate of the IMC that is formed between electrolytic nickel finishes and SnPb is however basically the same as for copper finishes and SnPb [55]. Figure 19 below shows the growth rate of the intermetallic layer between different nickel surfaces and SnPb solders when aging at 125 °C and 150°C [55].
3.5.4.3 Lead free and copper
As the growth rate of intermetallic layers in SnPb solders depends on the Sn content it might seem like the lead free solders would have a higher growth rate than SnPb solders. However, the studies show contradictory results. Some studies say that SnAg solders have a slower growth of IMC than SnPb but for lead free solders containing copper the growth rate is higher than SnPb during reflow. However, copper containing lead free solder joints has the same growth rate of the IMC during aging as SnAg solder joints [55].

The intermetallic formation and growth were studied between the alloys Sn-3.2Ag-0.8Cu, Sn-3.5Ag and Sn-0.7Cu and a copper pad. Coupons of solder joints, prepared by melting some of each solder alloy on a copper-plated circuit board, were subjected to a thermal aging test for 20, 100, 200 and 500 hours at 70, 100 and 150ºC. The results for the solders that were aged in 150 ºC are presented in figure 20. As seen the growth rate differs depending on chemical composition and the slowest intermetallic growth was for Sn-3.5Ag. The Cu₃Sn are identified by diamonds and the Cu₆Sn₅ are identified by squares [13].

![Graphs showing intermetallic growth](image)
3.5.4.4 Lead free and Nickel
Several studies show a slower growth rate of the intermetallic layers when soldering a lead free solder joint to a nickel surface compared to soldering a leaded solder to a nickel surface. However, there are also studies that show the total opposite. As when soldering lead free to copper the growth rate of a IMC between a lead free solder joint and a nickel surface depends on the chemical composition of the solder joint [55].

3.6 Other problems to consider in a transition to lead-free
As mentioned in previous chapters there are several problems to consider in a transition to lead free. Some are purely logistical but there are more material related problems like Kirkendall voids, whiskers and pad cratering.

3.6.1 Kirkendall voids
A Kirkendall void is a cavity caused by diffusion. When soldering, the metal in solder paste will diffuse in the solder joint and the rate depends on the materials involved. The diffusion process makes it possible for an atom to move from their original place into the crystal vacancies of another material. The vacancies will therefore appear to be the moving feature and they tend to coalesce and form of voids or pores. The Kirkendall voids can start growing during the formation of IMC and they can cause brittle fractures.

The Kirkendall voids are most likely formed when the joint is exposed to high temperature aging. The risk of the voids increase with increasing temperature and therefore it could be a concern in the transition to lead free, due to the higher process temperatures.

3.6.2 Whiskers
The creation of tin-whiskers is a phenomenon that can occur when dealing with tin. Metal whiskers are single crystal needles that suddenly can start growing out of a metallic surface. If this phenomenon occurs in a circuit board it means a catastrophe, because whiskers are electrically conductive and can cause short circuits. Figure 21 shows what whiskers could look like
The phenomena whiskers are not fully understood yet, but it is seen that whiskers start to grow when compressive stresses (for example, mechanical stresses and thermally induced stresses) are present. Whiskers can appear not only in tin but also in zinc, gold and silver.

In a transition to lead-free the problem with tin-whiskers will remain a potential reliability threat. Previously, lead has been used as a coating to prevent the formation of tin-whiskers. When the lead is removed out of the solders, the risk of tin whiskers might increase. If a whisker starts growing on a leg of a component it may grow over to another leg and cause a short.

![Image of whiskers](image1)

**Fig. 21 The material phenomena Whiskers [73].**

### 3.6.3 Pad Cratering

Lead free solders are stiffer than leaded solder joints, and some of the PCB used for lead free soldering are also more brittle than the most common board used for leaded soldering, FR4. This coupled with the higher temperatures involved with a reflow for the lead free processes causes a higher strain to the PCB, can cause a cohesive failure underneath the BGA pads. This is called pad cratering and is showed in picture 22 [75].

![Image of pad cratering](image2)

**Fig. 22 Different failure modes for a PC, type, A and G shows pad cratering [75].**
4 Materials and Methods

4.1 Test plan
When planning the experiment the objective was to make the test as realistic as possible, therefore the processes as well as the handling of the assembled circuit boards were studied, and the test plan was built up on these studies. The goal with the experimental part of the project was to investigate how the rework affected the brittleness of the solder joint. After mounting, reworked performed on some of the components, after that some were cross-sectioned and analysed in microscopes and some were sheared and analysed in microscopes.

4.1.1 The test vehicle
The leaded reference materials (solder pastes, solder material and surface finishes) were the ones that were most commonly used at SMW today. The lead-free material, SAC305 were chosen because it was commonly used at the market, it was easy to access, it was the most tested material in the SAC family and it was of interest for SMW.

4.1.1.1 The board
The board used for this test was designed as an actual board, used in SMW products, the footprints intended for the surface mounted component was of different types and various sizes. To fit the shearing device only parts of the pattern were used to place components on, see figure 23.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>The dimensions of the boards were 230 x 160 mm and the thickness is 2 mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBC Material</td>
<td>The boards were made of a high Tg/Td laminate, 370HR, FR4. The same type of boards was used both for the lead free process and the leaded.</td>
</tr>
<tr>
<td>Build-up</td>
<td>The boards were multilayer printed boards with 12 copper layers.</td>
</tr>
</tbody>
</table>
Surface finish

The surface finish that was chosen for the lead free process was HASL/SN100C and for the leaded process it was HASL/SnPb. These surface finishes are commonly used in the electronic industry today.

Solder material

The solder paste used for the lead-free process was LFM-48W TM-HP (flux content 12% Alloy: SAC305) from Almit. For the leaded processes it was Solderel – DMH0520 Sn62Pb36Ag2 90% flux (25-45 microns).

Fig. 23 The left picture shows the original layout of the board and the left picture shows the patterns on which the component were going to be placed.

4.1.1.2 The components

The test vehicles used for this study were printed circuit test assemblies with two kinds of surface mounted packages; Ball Grid Array, BGA, and Quad Flat No-Lead, QFN. QFN is a component that is popular for its thermal integrity and good electrical performance and the BGA components are of interest due to the fact that studies have shown that the BGA joints are prone to brittle fractures, and since lead-free joints will increase the risk of brittle fractures, it makes the component even more interesting to study.

QFN:
The size of the QFN components were 7x7 mm. The cooling pad was 5.3x5.3 mm and the peripheral pads were 0.305x0.66 mm, see picture 24. The surface finish of the QFN pads was immersion tin.
4.1.1.3 The component placement
As mentioned, previous studies have shown that a temperature above 60ºC induces the growth of the intermetallic layer [1]. Therefore, it was of high interest to investigate the effect of rework. Due to the heat spread over the board adjacent components can be affected during a rework. When planning the experiment it was of high significance to get a result of the effect on closely surrounding components as well as components situated further away from a reworked component, and compare them. Even though the adjacent components are not exposed to the same degree of heat as the reworked component itself, it is still heated up to a temperature above 60ºC, causing the IMC to grow on all components of the board.

In order to see how the adjacent components were influenced by the rework the component placement had to be carefully planed. The circuit board were split into three parts prior to the rework of the BGA components. The components that were not reworked had to be placed as similarly as possible on each part (from the same distance to the reworked BGA), so that the result from the shear testing and microscopes of part 1:1, 1:2 and 1:3 would be comparable to each other, see figure 25 and 26. The boards were split in three because it was necessary to have enough statistical results for the shearing results.
BGA A: Reworked component
BGA B: Adjacent component
BGA C: Distant component

Fig. 25 The picture shows the placement of component A, B, C and the QFN.

Fig. 26 The picture shows the placement of component A, B, C and QFN.
### 4.1.2 Processes

During the experiment all components were first assembled to the board through a solder process, then some of the boards were also exposed to rework. All boards were exposed to either one of the following treatments.

**Assembled:** Assembled

**Rework 1:** Assembled + 1 BGA rework.

**Rework 2:** Assembled + 2 BGA rework

A board that went through assembly was the reference and it would give an indication of how the intermetallics and thereby the properties of the joint would be like in the best case scenario after going through the mounting processing. The components that went through rework 2 were considered to obtain the worst case scenario. As a rework process includes a removal and an insertion of a BGA component, the component has actually been exposed for two reflow cycles for each rework process. All boards were also preheated before assembly for 6 h in 100°C, as it is a standard procedure to avoid delamination of the boards. Picture 27 illustrates a chart that shows what type of processes the different test vehicles went through.

![Diagram](image)

*Fig. 27 The chart shows what type of processes the different test vehicles went through.*
4.1.2.1 Assembly
As mentioned in previous chapter a vapour phase oven is used when soldering at SMW. The soldering process at SMW follows a normal procedure, see picture 28. The leaded test vehicles were assembled in one oven and the lead free in another, both ovens were vapour phase ovens. The lead free oven soldered two boards at a time. The temperature profiles used were different for the leaded and the lead free test vehicles (see appendix B).

\[
\begin{align*}
\text{Pre heat the boards (60ºC for 6 h)} & \\
\text{Apply solder paste on boards using stencils} & \\
\text{Place components on boards} & \\
\text{Solder} & \\
\text{Wash boards} & \\
\text{Inspect} & \\
\end{align*}
\]

*Fig. 28 A flow chart over the soldering process at SMW.*

4.1.2.2 Rework
When performing rework a temperature profile had to be developed. Usually, the manufacture of the solder paste specifies the temperature profile for the specific solders and this temperature profile is modified slightly to fit the board that the rework is preformed at. This is done by soldering thermocouples to the board. The thermocouples are soldered to key locations of the component that is going to be reworked. By using thermocouples the temperature of the different key locations were obtained. If the key locations did not reach the temperatures that they were supposed to the temperature profile was modified to ensure proper temperatures.
The cleaning with solder wick was also not preformed. When cleaning the surface with solder wick the board is exposed to heat. The heat exposure is very direct and does not spread over the board. Before simplifying the process and excluding the cleaning with solder wick from the rework process the heat spread was measured. It turned out that the surrounding pads were only heated a couple of degrees. Therefore, this step could be ruled out of the rework process.

Since a BGA rework takes several hours to perform, the process of the rework was simplified. The BGA that were reworked were not properly cleaned with solder wick between the removal and the insertion of the same component. Also, the same component was actually removed and afterwards inserted again. The intermetallics of the removed BGA were therefore not analyzed.

4.1.2.3 Naming the boards
Two copies of all types of boards were obtained. The reason to making two boards of each kind was to obtain enough statistical results for the shearing results. This means that there were six copies of each type of BGA A, BGA B, and BGA C as well as QFN. The leaded boards were numbered 7-13 and the lead free were numbered 20-26. Board nr 26 was used when developing the temperature profile for the rework and board nr 7 was used as a waste board went trying the shearing device. The following boards when through the following processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Lead:</th>
<th>Lead free:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembled</td>
<td>8 and 9</td>
<td>20 and 21</td>
</tr>
<tr>
<td>Rework 1</td>
<td>10 and 11</td>
<td>22 and 23</td>
</tr>
<tr>
<td>Rework 2</td>
<td>12 and 13</td>
<td>24 and 25</td>
</tr>
</tbody>
</table>

Since the boards were split in three they were also named part 1-3. A reworked leaded BGA component A from part 1 that went through 1 rework was therefore named; 10_1_A.
4.1.3 Methods for analysing results

The method used when analyzing the results is presented in a flow chart in figure 29:

Fig. 29 The flow chart shows the method used for analysing the results.

One component of each type (total nr of 24) were cross-sectioned and prepared so that an analysis of each sample could be preformed using a stereomicroscope (SM), an optical microscope (OM) and a Scanning Electron Microscope (SEM).

- In SEM the intermetallic layers were measured and the chemical composition was analysed.
- In OM and SM the cross-section of the component was observed, information about the solder joint sizes and shapes were noted as well as the presence of voids. The fractured surfaces of the boards and the components were also examined using an SM and an OM.

The heat spread over the boards when performing rework was filmed using an IR camera. One film sequence was recorded when doing a rework of a leaded component and one film sequence was recorded when doing a rework of a lead free component. To obtain the exact values of the heat spread over the board, thermocouples were mounted into the board in the places were the components were situated. After that a lead free as well as a leaded rework profile was performed and the temperatures were logged and analyzed.
A shear test was performed to evaluate the effects of the intermetallics and how they affected the reliability of the solder joints as a function of exposure to heat. A shear test is a low-cost test to perform when evaluating the reliability of a solder joint. There were five components of each kind were sheared in the shearing device.

4.1.3.1 Microscopes

4.1.3.1.1 Optical Microscope (OM) and Stereomicroscope (SM)
As mentioned previously all fractures surfaces were analyzed in OM and SM. Both instruments were fitted with cameras. Visual examination was made with an optical microscopy with a maximum magnification of 100x and a stereo microscope with a magnification up to 50x.

4.1.3.1.2 Scanning Electron Microscope (SEM)
The SEM is used to get a higher magnification and better resolution than what is possible with OM or SM. It is also used for a chemical analysis of the sample.

Compared to an optical microscope that works with visible ray to create an image, a SEM uses electrons to create the image. Due to the shorter wavelength of the electrons the image for a SEM can be of higher resolution that an image created of an OM. The secondary electron detector allows the topography of the surface to be revealed while the electron backscattered detector gives contrast for the different kinds of elements present. Non conducting samples have to be gold coated to prevent charging [63].

Generally, when looking at a SEM picture of the cross-section of leaded or a lead free component with a electron backscattered detector it is easy to distinguish a difference. In the leaded BGA there are areas that come off as white in the picture and these areas are the lead. This huge difference can be seen in figure 30 below. The right picture is a SAC solder and the left one is a leaded solder. Both of them are soldered to a copper layer and the band in between the copper and the solder is an IM layer.
EDS is an analysis method that provides the user with information about the chemicals which are present in the observed object. This is done through identifying X-rays associated with a unique atomic structure [63].

### 4.1.3.1.3 Sample preparation for microscopes

In order to analyze the solder joints in OM, SM and SEM all components were cut in half and cast in epoxy. The epoxy was a mixture of the EpoFix Resin and EpoFix in a mixture of 15/2. The following steps were followed in the preparation process:

1. The two specimens were cut and cast in a mixture of epoxy resin adhesive, EpoFix Resin and EpoFix Hardener.

2. The epoxy was cured for approximately 12 hours.

3. Grinding was done by hand with a grinding machine. The grind paper used had a roughness of: 320, 600, 1200 and 4000 µm. The specimen was rotated 90°, to minimize scratches.

4. Polishing was done with diamond paste of 0.25 µm.

After this the samples were ready to be examined in OM. But before examining samples in a Scanning Electron Microscope, SEM the samples need to be etched and sputtered with gold. The etching was done with a mixture of $\frac{1}{4}$ acetic acid and ethyl alcohol and...
¾ parts of water. The sample was coated in a thin layer of gold in a *Blazers union SDC 040*.

### 4.1.3.2 Filming with IR camera during rework

An IR camera is a device that forms an image using infrared radiation. All objects emit a certain amount of thermal radiation as a function of their temperature. The higher the temperature of an object, the more infrared radiation it emits. The IR camera can detect the radiation and the software in the camera will form a temperature image. In this test the IR camera was used only to observe the heat spread over the board, however, the camera has the ability to obtain the precise temperatures of most objects.

### 4.1.3.3 Shear testing device

To evaluate the effect of microstructural variation on the joint strength of the components, a shear test was carried out. The research centre KIMAB has invented a method that can evaluate the risk of a joint to experience brittle fractures, by using this high-speed shear testing device. Unfortunately, the device could not shear the QFN components due to the large cooling pad of the component that are soldered to the board surface. Shearing of a pad of that size would require much higher max force that what KIMAB’s shearing device was designed for. The device can be seen in figure 31.

![KIMAB's shearing device and the high speed camera.](image)

The testing device is set up according to figure 32. It has a moving table that the test vehicle is placed on, a device tool, and another tool to knock off the components with.
When the vehicle is tested the table is moved towards the tool with a speed of 1 m/s which is a high speed to knock off a component of that size with.

The results are presented in force-displacement curves, which can be analyzed to find out more about the material properties. From the curves vital information can be obtained, for example; maximum force to failure, plastic/elastic deformation, total failure energy, and an indication of the materials brittleness. A high speed camera is incorporated into the shear system to control the testing procedure and monitor the fracture. The camera takes about 6000 frames per second. The boards are mounted so that each component is knocked off at the centre of one of the sides of the component [58].

4.1.3.3.1 Failure Mechanism
A failure in a solder joint are commonly caused by two types of stress; temperature variations that induces stress in the form of a low cycle fatigue or stiff joints that are subjected to rapid deformation caused by high impact forces.

When a solder joint is exposed to high strain rates like in a mechanical shock, the solder material behaves like a strong material causing the IMC to experience a high stress. In this situation the properties of the IMC are of high significance. The chemical composition and thickness of the IMC will therefore play a significant role in what type of fracture that will be observed. The shear test at KIMAB is a high strain rate test where the intermetallics play a great role [58].
4.1.3.3.2 Evaluation of force-displacement curves

During the shearing a computer records the force displacement giving a graph of the type that can be seen in picture 33. The maximum force required to failure is automatically detected as well as the velocity. In the graph it can clearly be seen where the initial contact was achieved. The latter peaks are a sign of vibration. The deformation consists of elastic and plastic deformation. For a brittle fracture the plastic deformation is small. The elastic deformation can be estimated by drawing a line from the linear part of the force displacement curve up to the corresponding force when the fracture occurs. The elastic energy at the fracture can then be presented by calculating the integral of the triangle. The plastic deformation energy is the total consumed energy minus the elastic energy, this can be calculated by taking the integral of the force-displacement curve and subtract the elastic energy. The ratio between the plastic and elastic deformation energy can then give information of how brittle the fracture was [58].

![Force-displacement curve](image)

*Fig. 33 shows a force-displacement curve obtained by KIMABs shearing device [58]*
4.1.3.3 Preparations before shearing

The PCB components were mounted to the test bench as shown in the figure 34. The knock-off tool is lowered to a correct height. The following steps are performed;

1. All components on each PCB were marked with a name
2. The test vehicle was mounted on the movable table
3. The table was moved away from the knock-off tool at a slow rate to a certain distance so that the knock-off tool would have time to reach its required speed before it hitting the component.
4. The samples were accelerated against the tool at the impact speed of approximately 1 m/s and the component is removed from the PCB. Due to the high speed the brittle failure should occur in the intermetallic.
5. A force-displacement curve was plotted and could be analysed, together with the film.
6. The remaining pieces of the components were removed and stored.

Fig. 34 The left picture shows how each component on board 13_3 were marked with an individual name and the right picture shows how the test vehicle was placed on the movable table.
5 Results

5.1 Time and temperatures

The information about the time and temperatures during the soldering and rework was obtained during the processes and it is presented below.

5.1.1 Temperature profiles during soldering

5.1.1.1 Lead

When soldering the components to the board the temperature profile presented in figure 35 was used. The time above liquidus was 89 seconds and the maximum temperature reached a value of 214°C, making the $\Delta T = 35 ^\circ C$.

![Fig. 35 The picture shows a temperature profile used for leaded soldering](image)

5.1.1.2 Lead free

When soldering the lead free boards the two boards were soldered at the same time. The temperature profiles were plotted during the process and presented as seen in picture 36. The rest of the lead free temperature profiles are presented in appendix B.
Fig. 36 The picture shows one of the temperature profiles used during the lead free soldering.

A summary of all the lead free test vehicles time and temperatures above liquidus during soldering are presented in Table 2.

Table 2 shows all the time and temperatures above liquidus for the lead free boards during soldering.

<table>
<thead>
<tr>
<th>Type</th>
<th>Test Vehicle</th>
<th>Alloy Melting point (°C)</th>
<th>Max temperature reached (°C)</th>
<th>ΔT</th>
<th>Liquidus time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead free</td>
<td>20 and 21</td>
<td>217</td>
<td>237</td>
<td>20</td>
<td>82</td>
</tr>
<tr>
<td>Lead free</td>
<td>22 and 23</td>
<td>217</td>
<td>237</td>
<td>20</td>
<td>104</td>
</tr>
<tr>
<td>Lead free</td>
<td>24</td>
<td>220</td>
<td>235</td>
<td>15</td>
<td>61</td>
</tr>
<tr>
<td>Lead free</td>
<td>25 and 26</td>
<td>217</td>
<td>237</td>
<td>20</td>
<td>93</td>
</tr>
</tbody>
</table>

5.1.2 Heat spread of the board during rework

5.1.2.1 Lead

The heat spread over the board was uneven over the board for approximately 3 minutes (185 sec), see figure 37. The maximum temperature difference between the reworked component and adjacent component was 82°C and the maximum temperature difference between the reworked component and the distant component was 88°C. The values are summarized in Table 3. The heat of the distant and the adjacent component was
approximately the same during rework. The information about the heat spread over the board was obtained by soldering thermocouples on the locations where the components were placed and then performing a rework. The logged temperature profile that was achieved when performing the rework is presented in appendix E.

Table 3 The maximum temperature of the different components of the boards

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum temperature (ºC)</th>
<th>Time above liquidus (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>220</td>
<td>65</td>
</tr>
<tr>
<td>B</td>
<td>138</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>132</td>
<td>0</td>
</tr>
</tbody>
</table>

![Fig. 37 The spread of the heat over the leaded board. The picture to the left shows a quite even heat spread and the picture to the right show an uneven spread of the heat over the board.](image)

5.1.2.2 Lead free

The heat spread over the board was uneven over the board for 165 seconds, see the figure 38. The maximum temperature difference between the reworked component and adjacent component was 67ºC and the maximum temperature difference between the reworked component and the distant component was 63ºC. This is summarized in Table 4. The heat of the distant and the adjacent component was approximately the same during rework. The information about the heat spread over the board was obtained by soldering thermocouples on the locations where the components were placed and then performing a rework. The logged temperature profile that was achieved when performing the rework is presented in appendix E.
Table 4 The maximum temperature of the different components of the boards

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum temperature (°C)</th>
<th>Time above liquidus (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>223</td>
<td>65</td>
</tr>
<tr>
<td>B</td>
<td>156</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>160</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 38 The spread of the heat over the lead free board. The picture to the left shows a quite even heat spread and the picture to the right shows an uneven spread of the heat.

5.2 Observations after mounting
There were no certain remarks after mounting except that on the lead-free boards the wetting seemed a bit poor. This could be seen on the patterns where no components were mounted.

5.2.1 Observation with X-radiography
After a soldering process some of the boards were examined using X-radiography. If the boards have more than 25% voids they can not be used. One board of each kind was observed and all of them had 0-15% voids and therefore they all passed. There were more voids observed on the lead free BGA components but the shape of the solder joints looked more even on the lead free than the leaded ones.

No bridging between the pads was seen on the QFN components. There were some quite large voids in the cooling pad, but not to many to not pass the test.
5.3 *Observations in microscopes*

5.3.1 *Dimensions and shape*

When examining components that were not mounted, a difference in size for the leaded and lead free solder balls could be seen with the naked eye, see figure 39. The lead-free solder balls were larger than the leaded ones. When the dimensions were measured in a stereomicroscopy and it turned out that the leaded BGA were 0.4 mm in diameter while the lead-free was about 0.7 mm. When removing the solder balls and measuring the solder surface on the component side leaded pads were 0.3 mm and the lead free were 0.5 mm.

![Fig. 39 The difference in size of the leaded and the lead free BGA components. The lead free component with larger solder balls is the left component.](image)

5.3.2 *Observations in OM*

5.3.2.1 *Observations on BGA components*

When examining the cross sections of the BGA joints in OM the following observations could be seen: There were a low void content in the joints. Of the 18 BGA components, 8 bumps were observed of each sample and a total number of 3 voids were observed on the leaded bumps whereas 5 voids were found on the lead free bumps. An example of a void can be seen in figure 40.
Fig. 40 shows a cross section of a two lead free BGA components. In the right one a void can be seen.

Generally, the lead free BGA seemed to be more even and round in shape than the leaded ones. The lead free had a non-solder mask defined pad on both sides of the solder. Whereas the leaded ones did have a solder mask defined pad on the upper side but not on the lower side. This can be observed in figure 41. A solder mask defined pad means that the solder is at the edge of the copper pad, not around or within the pad.

Fig. 41 The picture shows a cross-section of different BGA bumps. The left picture shows a leaded BGA where the upper side is solder mask defined and the lower one is none solder mask defined. The right picture shows a lead free BGA that has a non solder mask defined pad on both sides of the joint.
5.3.2.2 Observations on QFN components
Picture 42 shows a cross section of a QFN component. The lower part is the copper of the board and the upper part is the pad of the component, made of copper with an immersion tin finish. The material between is the solder paste.

There were no remarks when observing the QFN components in the Optical Microscope.

Fig. 42 A cross section of a QFN component
5.3.3 Observations in SEM

In SEM the thickness of the intermetallic layer were measured and the chemical composition were analyzed using the EDS. Generally, the intermetallic layer were thick both at the interface between the solder and the board and solder and the component.

5.3.3.1 Intermetallic compounds formed at the interface between the solder and the board

5.3.3.1.1 Leaded

The chemical composition of the intermetallics between the board and the solder joint were the scalloped shaped Cu$_6$Sn$_5$ as expected. There were no sign of a second phase of intermetallics. The average thickness of the IMC was between 3 and 6.5 µm for the samples. The thickness could vary over the samples, sometimes as much as between 7-3 µm as be seen in figure 43. The thickest intermetallic layer was found on the samples that only went trough a soldering process. The thickness of the leaded intermetallic layers is presented in the figure 43.

The thickness of the intermetallic layers of the distant and the adjacent BGA was about the same. Sometimes the distant BGA had a little bit thicker IMC then the adjacent and sometimes it was the other way around.

Fig. 43 shows the thickness of the intermetallic layers formed on leaded BGA balls
Fig. 44 The pictures show the thickness of the intermetallics formed on the leaded BGA bumps. The top picture shows the assembled BGA, the middle shows the BGA exposed for 1 rework and the lower picture shows the BGA that was exposed for 2 rework. As seen in the pictures the thickness of the intermetallics are uneven.
5.3.3.1.2 Lead free

The chemical composition of the intermetallics showed between the board and the solder joint were Cu$_6$Sn$_5$. On one component a second phase of the intermetallic layer was seen, Cu$_3$Sn. The component was an adjacent component exposed to two reflows. The two layers can be seen clearly in picture 45. The lower layer is Cu$_3$Sn. Cu$_6$Sn$_5$, were around 3 µm while the Cu$_3$Sn compound were around 3-4 µm thick.

![Image](22-3-B1.png)

Fig. 45 Two phased of the intermetallic compounds, Cu$_3$Sn and Cu$_6$Sn$_5$, was found on a lead free solder joint.

The average thickness of the IMC was between 3.5 and 7 µm for the samples. The layers were more even than the leaded ones. The thickness of the intermetallic layers of the distant and the adjacent BGA was almost the same for all the samples, see figure 46.

![Image](image.png)

Fig. 46 shows the thickness of the intermetallic layers formed on lead free BGA balls
Fig. 47 The thickness of the intermetallics formed on the leaded BGA bumps. The top picture shows the assembled BGA, the middle shows the BGA exposed for 1 rework and the lower picture shows the BGA that was exposed for 2 rework.
5.3.3.2 Intermetallic compounds formed at the interface between the solder and the component at BGA components

An EDS analysis in the SEM showed that the pad of the component was surface coated with electrolytic nickel. If the copper surface had been coated with ENIG phosphorus, it would have been seen in SEM. In this case, Ni and copper could be seen. The intermetallic formed at the component side was Ni$_3$Sn$_4$.

![Fig. 48 is a diagram of an EDS analysis made at the interface between the solder and the component of a BGA component.](image)

5.3.3.2.1 Leaded BGA component

The intermetallic layer of a leaded BGA component that had been mounted on a board (no reflows) had an intermetallic layer of Ni$_3$Sn$_4$ was around 3 µm and a nickel coating of around 8µm, see figure 49. The leaded component that went through 2 reworks had similar values as one that did not go through any reworks.

![Fig. 49 The cross-section of a leaded component that has not been exposed to any reflows. The intermetallic layer is around 3 µm and the nickel coating around 8µm](image)
5.3.3.2.2 Lead free BGA component

The intermetallic layer of a lead free BGA component that had been mounted on a board (no rework) had an intermetallic layer of Ni$_3$Sn$_4$ that was around 18 µm and a nickel coating of around 10 µm, see figure 50. The intermetallic layers of the lead free component that went through 2 reworks had similar values as one that did not went trough any rework.

Fig. 50 The cross-section of a lead free component that has not been exposed to any reflows - just mounting. The intermetallic layer is around 18µm and the nickel coating around 10µm
5.3.3.3 Intermetallics formed on QFN components

The intermetallics of the leaded QFN were thick and uneven. Sometimes they ranged between 9-6µm on one sample, see figure 51. The lead free intermetallics were a little bit thinner but still in the range between 3-5µm. The thickness of the intermetallic layers of the rework and only assembled QFN components were basically in the same range for all the samples of the same type.

![IMC thickness - QFN](image)

Fig. 51 The thickness of the intermetallic phases of the leaded and the lead free QFN components

![Fig. 52 The intermetallic compounds of the leaded (left) and the lead free (right) QFN components](image)
5.4 Shear test result

5.4.1 Fracture surfaces
When analyzing the fracture surfaces an optical microscope as well as a scanning electron microscope was used. The results are presented below.

5.4.1.1 Leaded fracture surfaces
All the fracture surface of the leaded BGA solders looked basically the same. It did not matter if it was an adjacent or distant component or if it was a component that went trough zero or two reworks.

Almost all solder balls (94-100%) were still stuck to the test vehicle after the shearing, which means the fracture was created at the solder joint/component interface. The fracture surfaces looked basically the same on all of the solder joints, see picture 53. The colours of the picture are an effect caused by the optical microscope and it is misleading, in reality the colour is silver/grey instead of golden.

![Fig. 53 Both pictures show the same BGA solder ball. The ball is still stuck to the board after shearing](image)

To be sure of the nature of the fracture a SEM analysis was preformed. When analyzing it became clear that the surface had large dimples which is characteristic for a ductile fracture. This can be seen in picture 54 and in a closer magnification in picture 55.
Fig. 54 A leaded BGA that was left on the test vehicle after shearing. The fracture surface shows dimples which is a sign of a ductile fracture.

Fig. 55 A leaded BGA that is left on the test vehicle after shearing. Large dimples can be seen at the fracture surface, indicating a ductile fracture. The picture is a magnification of picture 54.

The difference in height that was clearly seen in picture 53 was probably a sign of a cup cone fracture. A cup-cone fracture was also observed when examining the fracture surface on the component side (see picture 56 and 57) in both in the optical microscope and SEM. Picture 56 is a picture taken with an OM. At the picture is appears as if the surface has a difference in height.
When examining the fracture surface of the component side in SEM the same kind of phenomena's were seen as on the fracture surface of the board side. The cup and cone behaviour as well as the dimples confirmed the ductile fracture.

Fig. 57 The picture shows the leaded fracture surface on the component side after shearing. A cup cone behaviour as well as large dimples can be seen at the fracture surface, indicating a ductile failure.
EDS analysis in the SEM showed Ag, Pb, Cu and Sn. Since Pb is present the fracture has to be between the intermetallics and the solder balls. More detailed information about the EDS analysis is seen in appendix G.

5.4.1.2 Lead free fracture surfaces
The majority of the boards had 20-50% of the solder balls stuck to the board after shearing. Fractures were therefore present at both the solder ball/component interface as well as the solder ball/circuit board interface. It did not matter if it was an adjacent or distant component, or if it was a component that went trough zero or two reworks, the fracture surface and location of fracture were still the same.

The first solder balls were damaged by the knock off tool and could therefore not be analysed. A damaged solder ball can be seen in figure 58.

![Picture 1 shows the a EDS analyze of the leaded fracture surface](image1)

**Fig. 58 A fracture surface that has been damaged of the knock off tool.**
The fracture surfaces of the solder that was still stuck to the circuit boards looked as if they were of brittle nature in the optical microscope, see figure 59. The mating fracture surface also looked like as if it were of brittle nature. The left picture shows three circles which could be a sign that the fracture did not happened instantaneously but in sub steps.

![Fig. 59](image1) The left picture shows a solder ball that is still stuck to the board after the shearing. The right picture is taken at a component on a spot were the solder ball has been knocked off.

When observing the fracture surfaces closer in SEM, a mixed fracture was observed, see figure 60. Some areas showed ductile dimples and other showed intercrystalline brittle fracture.

![Fig. 60](image2) The left image shows a solder ball that is still stuck to the board after the shearing and the right image is taken at a component side. Both surfaces showed a mixed fracture.

The circled areas in figure 61 shows intercrystalline brittle fracture and the other areas shows dimples and thereby a ductile fracture.
Fig. 61 The picture shows a mixed type of fracture of the lead free samples. The circled areas show intercrystalline brittle fractures and at the other areas dimples can be seen.

An EDS analysis showed that at some areas Sn, Ag, Cu and Ni was present and in some areas it was only Sn and Ag that was present. This shows that the fracture appeared in the intermetallic layer, either in the Nickel/intermetallic interface or in the solder ball/intermetallic interface. The result of the EDS analysis is shown in figure 62.

Fig. 62 The EDS analysis of the lead free fracture surface showed that the fracture happened in the IM layer.

The fracture surfaces of the solders joints that were stuck to the component after shearing still had their copper pads stuck to the balls. It was clearly seen that these fractures did not appear in the intermetallic layer, since both the copper pad and pieces of the board could clearly be seen in the optical microscope, see figure 63.
Fig. 63 The picture shows a component that still has some solder balls stuck after the shearing. As seen the copper pads are also left at the interface as well as parts of the board.

5.4.2 Results from shear testing

5.4.2.1 Leaded shear results
For the leaded components that were just assembled the values of the maximum force varied from 33 to 52 N for component B and C as seen in figure 64.

Fig. 64 The maximum force of the leaded components that were only assembled
For the leaded components that were exposed to one rework the values of the maximum force varied from 33 to 53 N for component B and C, see figure 65.

![1 rework graph](image1.png)

*Fig. 65 The maximum force of the leaded components that were reworked one time*

For the leaded components that were exposed to two reworks the values of the maximum force varied from 31 to 55 N for component B and C, see figure 66.

![2 rework graph](image2.png)

*Fig. 66 The maximum force of the leaded components that were reworked two times.*

The shear speed for the leaded component varied from 0.87 to 0.92 m/s for the leaded samples.
5.4.2.2 Lead free shear results
For the lead free components that were only assembled the values of the maximum force varied from 68 to 129 N for component B and C, see figure 67.

![Graph showing maximum force for assembled components](image1)

*Fig. 67 The maximum force of the lead free components that just were assembled.*

For the lead free components that exposed to one reflow the values of the maximum force varied from 66 to 133 N for component B and C, see figure 68.

![Graph showing maximum force for reworked components](image2)

*Fig. 68 The maximum force of the lead free components that were exposed to one reflow.*
For the lead free components that were exposed for two reflows, the values of the maximum force varied from 60 to 88 N for component B and C, see figure 69.

![Bar chart showing maximum force for components B and C after two reflows.](image)

**Fig. 69 The maximum force of the lead free components that just were assembled.**

The shear speed for the lead free component varied from 0.84 to 0.91 m/s for the lead free samples.

### 5.4.3 Shear footage

When evaluating the results from the shear testing the photos of the high speed camera were of great value. The videos showed a big difference of how the leaded and the lead-free components were fractured. For the leaded components the fractures were situated at the interface between the upper side of the BGA joints and the component. For the lead-free components the fracture was mixed, some balls were stuck to the components after shearing and some where stuck to the test vehicle.

Picture 70 shows how the leaded component got sheared off and picture 71 shows how the lead free samples got knocked off.
Fig. 70 The pictures show the shear sequence of the leaded BGA components. After shearing, all balls were stuck to the board.

Fig. 71 The pictures show the shear sequence of the lead-free BGA components. After shearing, some balls were still stuck to the component and some were stuck to the board.
The footage also showed a significant difference in how the components were knocked off. The bodies of the lead-free components were severely damaged before they were knocked off, see picture 72. Some of the leaded component bodies were also damaged but certainly not to the same extent as the lead free.

*Fig. 72 The picture shows how the shearing knock-off tool penetrates the lead free BGA components.*
## 6 Discussion

Table 5 shows a summary of the results obtained:

**Table 5: A summary of the results obtained**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specific</th>
<th>Leaded</th>
<th>Lead free</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time and temperatures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Preheated before soldering</td>
<td>60°C for 6 h</td>
<td>60°C for 6 h</td>
<td></td>
</tr>
<tr>
<td>2. Soldered</td>
<td>( T_{\text{max}} - T_{\text{M}} = \Delta T = 35^\circ C )</td>
<td>( T_{\text{max}} - T_{\text{M}} = \Delta T = 20^\circ C )</td>
<td>( T_{\text{max}} - T_{\text{M}} = \Delta T = 20^\circ C )</td>
</tr>
<tr>
<td></td>
<td>Time = 89 sec</td>
<td>Time = 61-104 sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max = 214°C</td>
<td>Max = 237°C</td>
<td></td>
</tr>
<tr>
<td>3. Preheated before rework</td>
<td>100°C for 24 h</td>
<td>100°C for 24 h</td>
<td></td>
</tr>
<tr>
<td>4. Rework (max temp)</td>
<td>Reworked = 223°C</td>
<td>Reworked = 220°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adjacent = 156°C</td>
<td>Adjacent = 138°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distant = 160°C</td>
<td>Distant = 132°C</td>
<td></td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solder area on component side (mm)</td>
<td>0.071 mm²</td>
<td>0.20 mm²</td>
<td></td>
</tr>
<tr>
<td>Solder ball (mm)</td>
<td>0.4 mm</td>
<td>0.7 mm</td>
<td></td>
</tr>
<tr>
<td><strong>IMC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMC solder/board</td>
<td>3-7µm</td>
<td>3-7µm</td>
<td></td>
</tr>
<tr>
<td>IMC solder/component</td>
<td>3µm</td>
<td>18µm</td>
<td></td>
</tr>
<tr>
<td><strong>Shearing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location of fracture</td>
<td>94-100% stuck to board after shearing. Fracture occurred in IMC between solder and Ni surface finish</td>
<td>Fracture occurred in IMC between solder and Ni surface finish or under the copper pad of the board</td>
<td>Fracture occurred in IMC between solder and Ni surface finish or under the copper pad of the board</td>
</tr>
<tr>
<td>Nature of fracture</td>
<td>Ductile</td>
<td>Brittle/ductile in the IMC</td>
<td></td>
</tr>
<tr>
<td>Effect of rework</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Effect on adjacent or distant BGA</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

**Intermetallics**

The intermetallic layers were thicker than expected for both the leaded and the lead free BGA solders. This was not worsened during the rework processes for any of the different types. A thick intermetallic layer is usually caused by the time and temperature above liquidus, however, these values were normal for both processes.

The intermetallics formed on the solder/board interface were expected to be in the range of 0.5 to 3 µm, though some studies have shown BGA components with intermetallics up to around 6 µm. In these tests, however, the intermetallics were in the range of 3 to 7µm after mounting for both leaded and lead free. This was unexpected, especially since
the boards were soldered in a vapour phase oven and the time above liquidus seemed normal.

The shearing was performed almost half a year after the mounting of the components. The intermetallics could have grown during this time, however, most likely less than 1µm. The preheating of the boards before soldering and reworking could have had an effect on the thickness of the layers. As mentioned, the preheating of the board before soldering was 6 hours in a temperature of 60ºC and the preheating before rework was 100ºC for 24 hours. If comparing this with the growth rate of the IMC described in section 2.5.4 the IMC could have grown approximately 1µm during this time.

Though it was nearly neglectable the intermetallics of the lead free samples were little thicker than the leaded ones on the solder/board side. However, it shall be noted that measuring intermetallic layers in the SEM is an approximation especially in these tests since the intermetallics observed were relatively uneven.

The rework did not seem to affect the intermetallic growth noticeable for the leaded or the lead free solder joints. This could be due to the fact that the layers were already thick to start with. If the intermetallic thickness would have been of a more normal range (around 3µm) after mounting, the rework might have had a noticeable effect.

It was interesting that a second phase of the intermetallic layer was found on the lead free samples at the solder/board interface. If a second phase is present it increases the risk of brittle fracture. The fact that a second phase was found on the IMC of the lead free materials and not on the leaded samples correlates well with previous studies.

As mentioned the leaded and the lead free BGA components had almost as thick intermetallic layers at the solder/board interface. However, at the solder/component interface the nickel based IMC was a lot thicker for the lead free samples. As for the IMC in the solder/board interface the layer on the solder/component side was not thickened during rework. The fracture surfaces showed that the lead free solders failed in mixed brittle-ductile nature while the leaded ones were ductile.
The intermetallics of the leaded QFN were thick and uneven. Sometimes they ranged between 9-6µm on one sample. The lead free intermetallics were a little bit thinner but still in the range between 3-5µm. Again, it should be noted that measuring intermetallic layers in SEM is an approximation. However, it is interesting that the lead free intermetallics seemed a bit thinner and more even for the QFN. One of the differences between the BGA and the QFN components was that it was a neglectable amount of nickel present in the QFN components compared to the BGA components. Studies have shown that the chemical composition of the IMC in solder/component interface and the solder/board interface affects the growth rate of the IMC at both interfaces. This could indicate that the presence of nickel might have a more negative effect on the IMC growth rate for the lead free material used than the leaded.

Adjacent and distant components
The heat spread over the board was uneven for approximately three minutes both for the leaded and the lead-free solders. The temperature difference over the board, $\Delta T$ was higher for the leaded than the lead free ($\Delta T_{\text{SnPb}} = 88^\circ C$ $\Delta T_{\text{SAC305}} = 67^\circ C$). However, the lead free surrounding component was exposed to 18ºC-28 ºC higher maximum temperature then the leaded ones.

The heat of the distant and the adjacent component was approximately the same during rework. The three minutes uneven heats spread over the board did not have any noticeable affect of the intermetallic growth. This was confirmed when comparing the intermetallics of component B and C, for both lead free and leaded components, even though the lead free components were exposed to higher temperatures that the leaded ones during rework. The time above 100ºC was approximately 340 sec for both lead free and leaded and this was probably too short a time to have a noticeable effect.

Fracture surfaces
The fracture surfaces were ductile for the leaded samples and mixed for the lead free samples. This was not surprising due to the fact that lead makes the solder more ductile.

For all the leaded samples the fracture happened in the intermetallic compound in the solder/component interface. This means that the intermetallic layer between the solder and the component was weaker than the intermetallics formed between the solder and
the board. At the solder/component interface a nickel compound was present and at the solder/board interface copper compound were present. For the leaded samples the intermetallic layer consisting of copper compounds were thicker than the nickel compounds in the opposite interface, still the fracture appeared in the upper IMC. This could mean that the presence of nickel had a negative effect on the solder balls’ strength. However, the fracture could have occurred at the upper side due to the fact that the leaded solders had a solder mask defined pad at the component side and a non solder mask defined pad at the board side. This naturally means that the solder is stuck harder to the board side and therefore it is not strange that the fracture happened at the component side.

For the lead free samples the fracture happened in both the solder/component side and at the solder/board side. However, it was only at the component side that the failure occurred in the intermetallic layer. The intermetallic layer at the component side consisted of nickel and was thicker than the intermetallic copper compounds at the solder/board interface. The nickel finish under the solder/component interface was thicker than expected: 8–10 µm for leaded and lead free. If the nickel has a more negative effect on the growth rate of the lead free material than the leaded it could be the reasons as to why the intermetallic layer of the lead free component was so thick on the solder/component interface compared to the leaded ones.

For the lead free samples some balls fractured at the solder/board interface, under the copper pad. This was probably caused by the fact that the shearing device did not really shear the components but the component body were lifted after the knock-off tool had penetrated the components. In this way the failure was mixed (tensile/shear).

Shearing curves and footage
As mentioned, the footage also showed a huge difference of how the components were knocked off. The bodies of the lead-free components were severely damaged by the knock-off tool before they were knocked off. Unfortunately, this affected the force-displacement curves. The maximum force to failure and total failure energy were supposed to be a measurement of the strength of the solder joints but because the device tool damaged the body component so severely, the measured force is a measure of the
whole components strength (body and solder joints). When the deformation of the component occurs the body component takes up a lot of the energy and therefore measured values of the failure energy can also not be trusted.

The videos show that for the lead-free components the fracture can not be seen as a shear failure due to the fact that as the knock-off tool deforms the component on one side, the opposite side of the component rises. This means that the bumps furthest away from the knock-off tool are not really sheared. Their failure mode is rather mixed (tensile/sheared). Previously, the components that were sheared with KIMABs device were 4x4 components. In this test the components had 8x8 solder joints and it was clearly seen that a component of this size is not suitable for KIMABs shearing device.

The reason as to why the lead free solder joint showed such a great variety of maximum shear force was probably because the device knocked off the samples with a variation in shear speed for each time. The variation in shear speed probably affected how much the knock off tool damaged the component which affected the maximum shear force.

The three circles that were seen on the lead free samples with the optical microscope could be a sign that the fracture did not happened instantaneously but in sub steps. This might be caused by the fact that device weakened the solder joints before the final failure took place.

The shear results for the leaded samples had a much lower shear force than the lead free ones. This is due to the fact that the solder area on the components side of the lead free samples was twice as large as the leaded, see Table 5. Since the lead free samples had a greater solder area it was stuck harder to the component than the leaded components. Therefore it was natural that the deformation of the body component was much worse for the lead free components.

**The rework equipment**

The maximum temperature reached for the leaded and the lead free reworked BGA components only differed 3°C. The fact that the ΔT between the melting point and the
maximum temperature reached was lower for the lead free was that the rework machines top- and bottom heater could not handle much higher temperatures.

The top- and bottom heater had to work hard to perform the temperature profiles for the lead free rework. Table 6 shows the maximum temperatures obtained for the top- and bottom heater. As seen in the table the lead free top heater had a maximum value of 346°C which was about as high as the equipment could provide. The maximum temperature for the lead free reworked component only reached a maximum temperature of 223°C, which only is 6°C over the melting temperature.

Table 6: The maximum temperature of the top and bottom heater obtained during the leaded and the lead-free rework

<table>
<thead>
<tr>
<th></th>
<th>Maximum temperature, top heater (°C)</th>
<th>Maximum temperature, bottom heater (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead free</td>
<td>346</td>
<td>320</td>
</tr>
<tr>
<td>Leaded</td>
<td>312</td>
<td>270</td>
</tr>
</tbody>
</table>

When performing the lead free rework the operator of the machine noticed that due to the higher temperatures the top and bottom heater had to reach, the machine needed a few minutes longer to cool down when performing the lead free rework.

**Source of errors**

The heat spread over the board might differ depending on the amount of copper in the board. The more copper layers the more efficient the heat spread. The board used in this test was a 2 mm thick board with 12 copper layers. A normal copper board used at SMW is 1.6 mm thick and has around 10 copper layers. This means that the board used in this test has a heat spread comparable with a normal SMW board.
7 Conclusion

In this thesis, the IMC between a solder (SAC 305 and SnPb) and a surface finish (SnPb and SN100C) were investigated. The effect of rework and the intermetallic growth and thereby the strength of the solders were also studied. The aim of the thesis was to see if there were any difference for the leaded and the lead free solder joints. The following conclusions were drawn regarding the intermetallic layers, the mechanical properties and the rework process:

- This thesis does not show that there will be an increase of brittle fractures in a transition to lead free.
- The adjacent and distant BGA were not damaged during rework
- Even though a transition to lead-free will require a more temperature sensitive rework process, rework can still be performed successfully with SMW’s equipments and skills of the personell.

Intermetallic layer and heat spread

- The heat spread over the board was only uneven for approximately 170 sec during the rework process, both for the leaded and the lead free boards.
- The adjacent and distant BGA will have approximately the same heat exposure and intermetallic growth during a rework, though the design of the board will have an impact on the heat spread.
- Rework did not have any significant impact of the intermetallic thickness.
- A second phase of the intermetallic layer was seen at one of the lead free solder joints and this could affect the mechanical properties of the joint.
- The intermetallic layers formed when soldering to electrolytic nickel finishes were weaker than the intermetallics formed to the copper finishes, both for the leaded and the lead free process.
- The intermetallic layer formed at the interface between a lead free solder and a nickel finish grew faster than an intermetallic layer between a leaded solder and a nickel surface. And on the QFN component, where there were almost no nickel present, the lead free intermetallic layer was thinner than the leaded ones. The presence of nickel could therefore, have a more negative effect of the IMC growth rate for the lead free material compared to the leaded.
The thickness of the intermetallics formed during mounting was much larger than expected and this might have affected the fact that the intermetallic thickness did not increase during rework. If the intermetallic layer was a little bit thinner after mounting a small increase of the layer might have been seen during rework.

Shearing device

- The shearing device is not appropriate for a component with 8x8 solder joints. If the component is stuck to hard to the board the body of the component is damaged during shearing and the force/displacement curve will not be measure of the strength of joints but rather a measure of the strength of the whole component.
- It is important to have a fixed velocity when shearing
- The movie obtained from the high speed camera was of great interest when evaluating the force-displacement curves. Without the footage the damage of the body component would have been more difficult to notice.

Further studies

- It would be interesting to evaluate what happens to the lead-free solder joints and the intermetallic layers during vibration testing, thermal cycling and thermal shock testing. Some of this will be covered in further tests at SMW.
- It would also be interesting to make further investigations regarding if a thinner intermetallic layer would grow faster during rework.
8 Acknowledgements

This thesis was carried out Saab Microwave Systems at the department of Material Technology, DD/ME, from September 2008 – November 2009, through Karlstad University, the department of Mechanical- and Material Engineering. The thesis was a compulsory part of Masters Degree of Mechanical Engineering specialization in Materials.

First, I would like to thank my supervisor at SMW, Lena Kvist. She has helped me to get in contact with the right people and given me the opportunity to participate in meetings, conferences and seminars and been a support during the process.

I also want to thank Per-Erik Tegehall at Swerea IVF which not only has helped me supplying me with literature, but has also been a great support throughout the whole process.

I also want to give a special thanks to Stefan Månbladh who performed the rework and Ingemar Hernefjord who performed the SEM investigations.

There are several people at SMW that have been a great support, supplying me with information and knowledge about SMW and their work there. Therefore, I would also like to thank: Daniel Carlsson, Christer Marklund and Peter Widén.

I also would like to thank some people at Swerea KIMAB: Christer Jörgensson, Håkan Thoors, Tag Hammam who were involved with the shear testing. Ulla Gudmunds Ohlsson who was involved with the surface preparation and finally Eva Lindh-Ulmgren and Margareta Nylén who helped me to get in contact with the right people at Swerea KIMAB.

I also would like to thank my tutor Christer Burman and my examiner Jens Bergstöm, from Karlstad University for giving me feedback during the process.

My last thank you goes out to Christian Olausson and Christer Bjurek at SMW for giving me this opportunity.
### Abbreviations & Definitions

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGA</td>
<td>Ball Grid Array, surface mounted component with balls of solder underneath</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>ENIG</td>
<td>Electoless Nickel/ Immersion Gold</td>
</tr>
<tr>
<td>EQS</td>
<td>Research Centre is collaboration between Swerea IVF, Swerea KIM AB and companies in the electronics industry</td>
</tr>
<tr>
<td>FR4</td>
<td>Flame Resistant 4. A fibreglass and epoxy substrate material used in circuit boards</td>
</tr>
<tr>
<td>HASL</td>
<td>Hot Air Solder Levelling</td>
</tr>
<tr>
<td>I-Ag</td>
<td>Immersion Silver</td>
</tr>
<tr>
<td>IMC</td>
<td>Intermetallic Compound</td>
</tr>
<tr>
<td>I-Sn</td>
<td>Immersion Tin</td>
</tr>
<tr>
<td>IVF</td>
<td>Industrial Research and Development Corporation, the Swedish engineering industry’s research centre.</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Boards</td>
</tr>
<tr>
<td>QFN</td>
<td>Quad Flat No Lead, surface mounted component</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>QFP</td>
<td>Quad Flat Pack</td>
</tr>
<tr>
<td>RoHS</td>
<td>Restriction of the use of Hazardous Substances</td>
</tr>
<tr>
<td>SAC</td>
<td>SnAgCu, Tin-Silver-Copper</td>
</tr>
<tr>
<td>SMW</td>
<td>Saab Microwave Systems</td>
</tr>
<tr>
<td>$T_d$</td>
<td>Decomposition Temperature</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Glass transition temperature</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
</tr>
</tbody>
</table>
10 Bibliography

Saab

1. L.Kvist, Saab Microwave Systems


4. Observation of the rework at SMW. S.Månbladh, Saab Microwave Systems. 2008-09-25

5. Observations when preparing samples at SMW. Peter Widén, Saab Microwave Systems. 2008-10-13


IVF

7. Meeting at IVF research centre. Per-Erik Tagehall, IVF 2008-09-18

KIMAB


11 Reference list

   [http://extra.ivf.se/eqs/dokument/7%20pet6005.pdf](http://extra.ivf.se/eqs/dokument/7%20pet6005.pdf)


   [http://www.3ktehdas.com/uutiset/Next_05.pdf](http://www.3ktehdas.com/uutiset/Next_05.pdf)
10. Fubin Song, F, Jeffery C.C. Lo, Jimmy K.S. Lam, Tong Jiang, S. W. Ricky Lee. *A Comprehensive Parallel Study on the Board Level Reliability of SAC, SACX and SCN Solders*. Hong Kong, Hong Kong University of Science and Technology.


13. T.A. Siewert *Formation and Growth of Intermetallics at the Interface Between Lead-free Solders and Copper Substrates* USA: Colorado School of Mines
   [http://www.boulder.nist.gov/div853/Publication%20files/NIST_Apex94_Siewert.pdf](http://www.boulder.nist.gov/div853/Publication%20files/NIST_Apex94_Siewert.pdf)


15. Tz-Cheng Chiu, Kejun Zeng, Roger Stierman and Darvin Edwards, Kazuaki Ano *Effect on thermal aging on board level drop reliability for Pb-free BGA Packages* Texas Instruments Japan, Ltd.

17. D. Hillman, M, Wells and K. Cho *The impact of Reflowing A Pb-free Solder Alloy Using A Tin/Lead Solder Alloy Reflow Profile On Solder Joint Integrity* USA; Cedar Rapids Iowa.


38. Dr. Benlih Huang and Dr. Ning-Cheng Lee *Prospect of Lead-free alternatives for Reflow Soldering*.


48. E. Tolentino *Reliability centric design for optimum availability of network elements.* Foundation of Technologies, Juniper Networks.


51. Rework of QFN – No Compromises
   http://www.finetech.de/enid/Rework__Repair/Rework_of_QFN--_No_Compromises__ql.html
   Finetech, last visit 2008-11-25.


53. Terry Davis. The back-end process: Step 9 QFN Singulation

54. Hans Danielsson, Välj rätt ytbehandling för blyfria mönsterkort.


57. Jeff Ferry. Who is afraid of lead-free rework www.circuitassembly.com


60. Rüdiger Martini, Herbert Streckfuss GmbH. Ångzonslödning blyfritt alternativ.

   www.solder.net/technical/LFbga3.asp Last visited 2009-09-19


75. Ahmad M, Burlingan J, Guirguis C. *Pad cratering under BGAs on PCBs*. PCB 007

http://www.pcb007.com/pages/zone.cgi?a=51651
12 Appendix A

12.1 RoHS and WEEE

The directive on the restriction of Certain Hazardous Substances, RoHS was taken on in February 2003 by the European Union. The July 2006 the directive took effect and was required to become a law in each member state of the European Union.

The RoHS directive restricts the use of hazardous materials in all type of electrical and electronic equipment. The hazardous materials include lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), polybrominated diphenyl ether (PBDE). The RoHS directive is closely related to the WEEE directive.

The aim of the Waste Electrical and Electronic Equipment (WEEE) directive is to reduce the massive amount of toxic that is released with electrical and electronic waste. The directive also intends to improve the knowledge of the recycling and recovery of the electrical products. The directive is in effect for all companies in EU that sells, distributes, and produces electronic and electrical devices.

12.2 EQS

The research center, EQS Centrum started during spring 2008. The centre is a collaboration between Swerea IVF, Swerea KIM AB and companies in the electronics industry. Their objective is to develop tools and provide knowledge to precipitating companies to achieve a more effective product development of electronic hardware. The centre wants to ensure quality of the electronic products during product development and also encourage the precipitating companies to work according to lean product development. The EQS members are companies that designs, manufactures and buys electronic hardware. Saab group is one of the precipitating members of EQS.

12.3 Glass transition temperature

The glass transition temperature, $T_g$ is the temperature at which an amorphous solid, goes from being hard and glassy to soft and more elastic.
When talking about $T_g$ in lead-free processes it is the $T_g$ of the circuit board that is interesting. The lead-free process requires higher temperatures when soldering and therefore it is important that the epoxy of the PCB does not melt. An epoxy that has high $T_g$ does not melt or expand as quickly as one with a low $T_g$. A material that change dimensions is not desirable in a material used for this application, a high $T_g$ is therefore requested in the soldering processes.

### 12.4 Decomposition temperature

The decomposition temperature, $T_d$ is when a material is being decomposed and loses 5% of its weight, at a certain temperature. Each soldering cycle that a material is being exposed for, is a contribution to the decomposition of the material.

A material that has a high $T_d$ value is preferred when a material is being exposed to a repeated number of soldering cycles.

### 12.5 Coefficient of Thermal Expansion

The coefficient of thermal expansion, CTE is a way to express the change in dimension of a material that occurs during temperature change. CTE is expressed as $1/\degree C$ which means how much a material expands for each degree of Celsius.

An alloy with a low CTE has a low dimensional change over a range of temperatures. These kinds of materials are very useful in applications where the material is exposed for a wide temperature range, like in aerospace.

All circuit boards expand when exposed to temperature changes. In the X and the Y direction the change is small because of the construction of the PCB; a glass fiber laminate keeps the material together in that direction. However, in the Z direction the CTE can be extremely high especially when reaching the $T_g$ value, because in this direction there is nothing in the material that is keeping it all together.

If an extremely high expansion occurs it can cause the circuit board to crack. Therefore, it is important to choose a material with a low CTE value in the z-direction for the circuit boards, especially when dealing with higher solder temperatures, as in a lead free process.
Appendix B

13.1 Temperature profiles for lead free soldering

13.1.1 Test vehicle 20 and 21

Recipe used
EP4108A SAC

with preheating

| Injection 1: | 55 cl |
| Preheating 1: | 160 °C |
| Condensation 1: | 0 sec |
| Preheating 2: | 190 °C |
| Injection 2: | 55 cl |
| Brazing: | 237 °C |
| Condensation 2: | 20 sec |
| Drying: | 15 sec |
| Extraction: | 100 sec |
| Cooling: | 95 sec |
| Max temp. reached: | 237,1 °C |
| Liquidus time: | 82 sec |

window width: 435 secs
Test vehicle 22 and 23

Recipe used
EP4108A SAC

with preheating

Injection 1: 55 cl
Preheating 1: 160 °C
Condensation 1: 0 sec
Preheating 2: 190 °C
Injection 2: 55 cl
Brazing: 237 °C
Condensation 2: 20 sec
Drying: 15 sec
Extraction: 100 sec
Cooling: 95 sec
Max temp. reached: 237.1 °C
Liquidus time: 104 sec

window width: 478 secs
13.1.3 Test vehicle 24

Recipe used
EP4108A SAC 2

with preheating
- Injection 1: 23 °C
- Preheating 1: 160 °C
- Condensation 1: 0 sec
- Preheating 2: 190 °C
- Injection 2: 55 °C
- Brazing: 235 °C
- Condensation 2: 20 sec
- Drying: 15 sec
- Extraction: 90 sec
- Cooling: 100 sec
- Max temp. reached: 235.4 °C
- Liquidus time: 61 sec

Window width: 511 secs

- User: TOMAS
- Cycle ID: blyfritt sac305 2pcb
- Comments:
Test vehicle 25 and 26

Recipe used
EP4108A SAC

with preheating

Injection 1: 55 cl
Preheating 1: 160 °C
Condensation 1: 0 sec
Preheating 2: 190 °C
Injection 2: 55 cl
Brazing: 237 °C
Condensation 2: 20 sec
Drying: 15 sec
Extraction: 100 sec
Cooling: 95 sec
Max temp. reached: 237.1 °C
Liquidus time: 93 sec

window width: 456 secs
14 Appendix C

14.1 Temperature profile for leaded soldering
Appendix D

15.1 Temperature profiles for rework

15.1.1 Lead free rework
15.1.2 Leaded rework
16.2 Heat spread over board – Leaded (Note: B=C and C=B)
17 Appendix F

17.1 Temp.profile Solder paste LFM48 TM-HP Sn-Ag-Cu

---

[Characteristics of the recommended temperature]

1. Can reduce the chip side solder balls.
   - Make the temperature rise of 50 - 100 degrees C, which the solder paste moves, be slow, it control the bleeding and reduce the solder balls.
   - Control the flux moves, and as the result, control the solder particle moves.

2. Advance in wettability
   - Triangular profile can control the oxidation of solder paste, components, hand at the preheat, and advance in wettability.

3. Gooduster of solder surface
   - Theuster of solder surface can be better because of control the oxidation, and advance in wettability.

4. Control the thumstone, and splattering of flux.
   - Set the temperature end of preheat be 100 degrees C. It make the temperature gradient to the peak be small.
   - Otherwise control the thumstone and flux splattering.

Thank You
18 Appendix G

18.1 SEM analysis

18.1.1 Leaded - PCB

Spectrum processing:
No peaks omitted

Processing option: All elements analyzed
Number of iterations = 2

Standard:
Ag  Ag  1-Jun-1999 12:00 AM
Sn  Sn  1-Jun-1999 12:00 AM
Pb  PbF2  1-Jun-1999 12:00 AM

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag L</td>
<td>0.62</td>
<td>1.55</td>
</tr>
<tr>
<td>Sn L</td>
<td>26.43</td>
<td>60.24</td>
</tr>
<tr>
<td>Pb M</td>
<td>29.26</td>
<td>38.21</td>
</tr>
<tr>
<td>Totals</td>
<td>56.31</td>
<td></td>
</tr>
</tbody>
</table>

---

100μm

Electron Image 1

18-xiii
18.1.2  Lead free – PCB spot 1

Spectrum processing:
No peaks omitted

Processing option: All elements analyzed
Number of iterations = 3

Standard:
C  CaCO3    1-Jun-1999 12:00 AM
Ni  Ni    1-Jun-1999 12:00 AM
Cu  Cu    1-Jun-1999 12:00 AM
Ag  Ag    1-Jun-1999 12:00 AM
Sn  Sn    1-Jun-1999 12:00 AM
Au  Au    1-Jun-1999 12:00 AM

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>3.66</td>
<td>32.95</td>
</tr>
<tr>
<td>Ni K</td>
<td>5.84</td>
<td>10.76</td>
</tr>
<tr>
<td>Cu L</td>
<td>9.34</td>
<td>15.91</td>
</tr>
<tr>
<td>Ag L</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>Sn L</td>
<td>42.87</td>
<td>39.09</td>
</tr>
<tr>
<td>Au M</td>
<td>1.30</td>
<td>0.71</td>
</tr>
<tr>
<td>Totals</td>
<td>63.57</td>
<td></td>
</tr>
</tbody>
</table>
18.1.4 Lead free – PCB spot 2

Spectrum processing:
No peaks omitted

Processing option: All elements analyzed
Number of iterations = 2

Standard:
C  CaCO3  1-Jun-1999 12:00 AM
Ag  Ag   1-Jun-1999 12:00 AM
Sn  Sn   1-Jun-1999 12:00 AM

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>0.91</td>
<td>46.23</td>
</tr>
<tr>
<td>Ag L</td>
<td>0.39</td>
<td>2.18</td>
</tr>
<tr>
<td>Sn L</td>
<td>10.09</td>
<td>51.59</td>
</tr>
<tr>
<td>Totals</td>
<td>11.39</td>
<td></td>
</tr>
</tbody>
</table>

![Spectrum Image]