Lead free electronics for demanding automotive applications

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1. Executive summary

The project has developed generic knowledge about potential reliability risks related to introduction of lead free soldering. Electronics for automotive applications are exposed to harsh environments with temperature cycling, severe vibrations and high peak temperatures under long required service life times and reliability demands are very high. The automotive industry will hence face a larger challenge as compared to producers of consumer electronics with relatively short expected life time and use in less demanding environments.

There exists much knowledge and long experience from use of tin-lead solders and methods available for ensuring reliability during construction, manufacturing and testing are based on this. Use of lead-free solders and solder surfaces are expected to introduce new failure mechanisms which need to be considered to ensure reliability for future lead-free products. The project has shown that the methods used today are often not sufficient to guarantee reliability after introduction of lead free soldering.

In parallel to the changeover to lead free soldering, there are also several other changes related to construction and manufacturing of electronic hardware. The project has identified other potential reliability problems that are not directly related to lead free soldering. Important changes are related to the continuous development of new component types and modification of older component types. These changes are primarily driven by functionality, often at the expense of decreased solder joint life time.

The project has identified and described critical failure mechanisms for relevant service environments. It was possible to define overlapping environments with relevance for all participating industrial segments i.e. for passenger cars, heavy vehicles and also aircraft applications.

Factors that will influence fatigue life were considered as most urgent for experimental validation in the project. Today, it is generally accepted that partial damage from sequential testing can be added to predict total life time (Palmer-Miners rule). However, lead-free solders do have time dependent properties that are accelerated by temperature and findings in the literature showed that the test sequence must be considered in order to correctly predict reliability and life time. For example, temperature cycling preceding vibration may lead to other conclusions as compared to initial vibration followed by temperature cycling.

The project has produced test vehicles with relevant components and also various combinations of solder and solder surfaces. Tin-lead solder was used as reference. The test plan included various sequences of ageing, vibration and temperature cycling but also combined vibration and temperature cycling. The test vehicles were equipped with Daisy chains and failures were continuously monitored during the testing. After testing, defect solder joints were analysed using metallography to identify occurring failure mechanisms.

Components with largest reliability risk include large ceramic passive components, BGA and QFN components. The IPC classification for automotive electronics was used to assess reliability and service life time considering number of temperature cycles until failure. Results showed that the large ceramic components could not fulfil the demands using lead-free solders whereas the smaller ceramic components fulfilled the requirements with good margin.

BGA components with 1mm pitch fulfilled the requirements for lead free with good margin and may be used also in more severe environments without reliability problems. BGA components with 1mm pitch are extensively used today for automotive applications although components with less pitch are getting more common. Testing of BGA components with 0.8mm pitch showed that requirements were fulfilled although without any margin. For some solder-solder surface combinations, the requirements could not be fulfilled. Use of thicker PCBs, larger components, lacquer and/or moulding plastics with lower CTE will increase the risk for reliability problems. Requirements for powertrain applications could not be fulfilled for the 0.8mm pitch components. For BGA components with a pitch less than 0.8mm, there is an impendent risk that the requirements will not be fulfilled even for less demanding environments. Smaller components may be less critical.

QFN components are increasingly used for automotive applications and these components fulfilled the requirements for lead-free with good margin. However, the results showed large scatter related to solderability problems after storing. It is important to guarantee sufficient wetting of solder surfaces on the side of the QFN component to ensure optimal reliability.

A general conclusion from the project is that many test standards used today are based on “best manufacturing practice” and consider manufacturing quality rather than reliability during long term use. It is recommended that testing for long term use should instead be based upon knowledge about expected failure mechanisms in relevant service environments. This will however, require much deeper knowledge about reliability aspects as compared to existing way of working. The project has contributed to increased knowledge about critical failure mechanisms and also reliability of different components exposed to cyclic load.

The project has also made an inventory of international knowledge in the field, a seminar with 30 participants was organized to spread information about current state-of-the-art and ongoing research in an international perspective. Research programmes on a national level do exist in US and Asia but today there is no ongoing common research within Europe. Some national programs do exist, in for example Belgium, however results from such programs are closed and there are no open information. The project has enabled unique national cross sectorial collaboration between suppliers/electronics producers, purchasers/vehicle producers and research institutes. The research institutes had the opportunity to deepen the knowledge within the field and this knowledge platform will be beneficial also for other companies that are facing challenges with lead free soldering. It is important however that this knowledge about reliability of electronics hardware can be maintained and further developed. Future collaboration on a national level is considered urgent.

2. Background

The changeover to lead-free soldering is considerably more complex considering electronics for automotive applications as compared to consumer electronics. Electronics in vehicles must have high reliability during long service life periods and this must be guaranteed before implementation of lead-free products. Vehicle electronics can be used for life critical functions such as airbags and brakes and relevant methods to test and verify reliability is of uttermost importance. Depending on the position of the electronic product, the environment can be aggressive with severe vibrations, large temperature variations, high peak temperatures and sometimes also high levels of humidity. Required service life for passenger parts are about 200 000-300 000 km and about 1 000 000-2 000 000 km for commercial vehicles.

Soldering with tin-lead have been the basis for manufacturing of electronics during the past 60 years and during this time comprehensive knowledge has developed regarding reliability and prediction of service life. There are however only limited experiences from lead-free alternatives and long-time use in harsh environments.

There are a large number of lead-free solders on the market, and these relatively new solders may introduce other failure mechanisms as compared to traditional tin-lead solders. Due to this, there is a large need to develop knowledge about failure mechanisms and possible reliability risks with lead free soldering. It is urgent that recommendations are issued to minimise the risk for reliability problems.

The EU commission has after strong pressure from the vehicle producers within Europe, taken the decision to prolong the exception from the ELV directive regarding lead containing solders. European vehicle manufactures have insisted that it is not yet technical feasible to implement lead-free electronics for demanding applications.

The changeover to lead-free soldering will affect not only the soldering process and the reliability of solder joints. It will also affect reliability of components and PCBs and therefore the complete development process. It is important that reliability can be ensured already during the design stage.

The existing project has identified and described failure mechanisms and environmental factors relevant for different automotive applications. Possible reliability risks related to design, manufacture and use have been considered.

3. Objective

The overall objective for the project has been to formulate generic knowledge about existing failure mechanisms and how these can be avoided. The project has also considered how relevant testing and life time prediction should be formulated. Knowledge developed in the project will lessen the need for extensive testing when new lead-free concepts are to be introduced. The results from the project will contribute with knowledge that can be used for future changeover to lead-free electronic products.

4. Project realization

The project was divided into 7 different work packages (WP). Each work package had defined goals and deliverables. The work packages are listed below.

WP1. State-of-the-art

WP2 Requirement specification and selection of lead-free concepts

WP3 Reliability risks with lead-free soldering

WP4 Evaluation and validation of identified reliability risks

WP5 Prototype and demonstrators

WP6 Result dissemination

WP7 Project management

5. Results and deliverables

5.1 Summary

Common methods to ensure reliability during design, manufacturing and testing of electronic products are not sufficient to guarantee reliability after the changeover to lead-free soldering. Electronics used in harsh environments, such as powertrain applications are most critical and will impose risk for reliability problems. However, with shrinking component size, the risk for reliability problems may be apparent also for less demanding environments such as the passenger compartment or the cab environment.

Component types with largest reliability risk include large ceramic passive components as well as BGA and QFN components. BGA components with 1mm pitch are commonly used today in automotive electronics although BGA components with less pitch are getting more common. QFN components are increasingly used and most QFN components used for automotive applications are relatively although the size is expected to increase.

The project has experimentally evaluated reliability for a number of components after lead-free soldering. The testing included ceramic passive components, BGA and QFN components.

The BGA and QFN components were manufactured with a new type of moulding plastics. CTE for this new plastic type can vary between 6-10ppm which will induce a certain uncertainty in the interpretation of the results. Solder joints for a component with moulding plastics with CTE of 6ppm will experience a reduction in life time corresponding to about 25-75% of the life time of a corresponding component with a moulding plastic with CTE of 10 ppm, depending of component type and PCB thickness.

The test vehicles that were evaluated had no lacquer, which is important to consider when interpreting the results since a lacquer may have a large negative effect upon reliability.

Many of the test standards used today are based on ”best manufacturing practice” and consider manufacturing quality rather than reliability under long-term use. Testing of reliability during long-term use should instead consider knowledge about expected failure mechanisms in relevant service environment. This will however require much deeper understanding of reliability aspects as compared to the traditional way of working. The existing project has contributed to increased knowledge about critical failure mechanisms and reliability of various components exposed to cyclic load.

5.2 Critical failure mechanisms

It is not only the reliability of solder joints that will be affected by a changeover to lead-free soldering. The increased soldering temperature will affect also the reliability of the components and PCBs. A large number of failure mechanisms will therefore be affected. Critical failure mechanisms that are related to lead-free soldering have been identified and described using the literature and are listed below.

- Formation of whiskers
- Delamination in components
- Fatigue fracture in solder joints
- Brittle fracturing in solder joints
- Plated through hole cracking
- Delamination in PCBs
- Formation of ”conductive anodic filament” (CAF)
- Pad cratering

5.2 Experimental evaluation

Experimental efforts in the project were focused on evaluation of risks for fatigue cracking of solder joints. Test vehicles with relevant design and commonly used components were produced and exposed to various combinations of temperature cycling and vibration. Testing was done using temperature cycling and vibration using sequential or simultaneous loading.

The test vehicles were equipped with Daisy Chains to enable in-situ monitoring of failure outcome. After testing, the solder joints were evaluated using metallography to identify causes of failures and failure initiation. The design of the test vehicles is shown in Figure 1.

The failure monitoring showed good agreement with the solder joint evaluations, solder joints with high electrical resistance showed clear occurrence of cracks in the solder joint.

The structure evaluations also revealed that the temperature cycling resulted in recrystallisation of the solder joint structure. Cracks were present within the soft recrystallized structure rather than along the intermetallic phases. The cracks propagated along the grain boundaries of the recrystallized grains, see example in Figure 2. Vibration loading did not result in any changes of the solder joint structure. The behaviour was similar for tin-lead and lead free solders.

Figure 3 shows results after temperature cycling for test vehicles containing components CR2512, BGA208 and QFN72. Red curves refer to components with tin-lead solder. The figure shows that the life time was significantly shorter for lead-free CR2512 and QFN72 whereas the lead-free BGA208 showed superior life time. Corresponding results are shown in Figure 4 after vibration loading. In general, vibration loading gave shorter life for lead-free as compared to tin-lead.

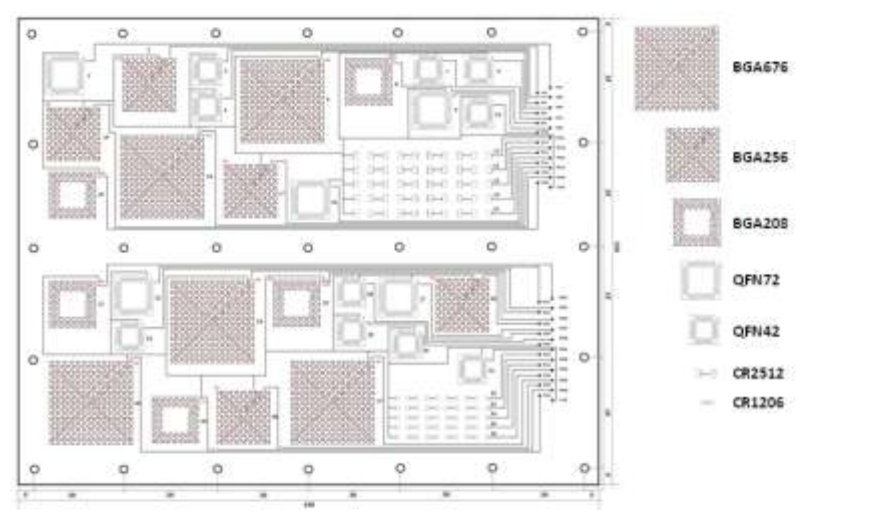

Figure 1. Test vehicle used for temperature cycling and vibration testing.

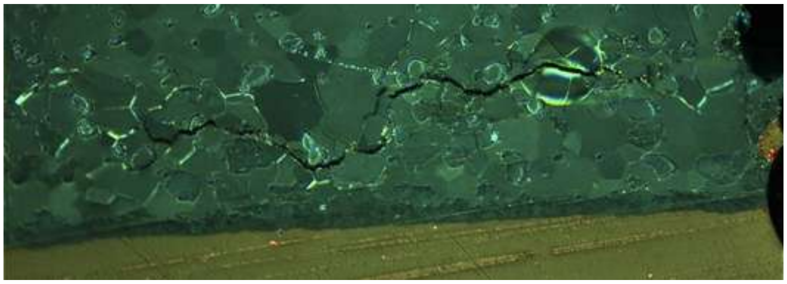

Figure 2. Example of crack propagation after temperature cycling of BGA component.

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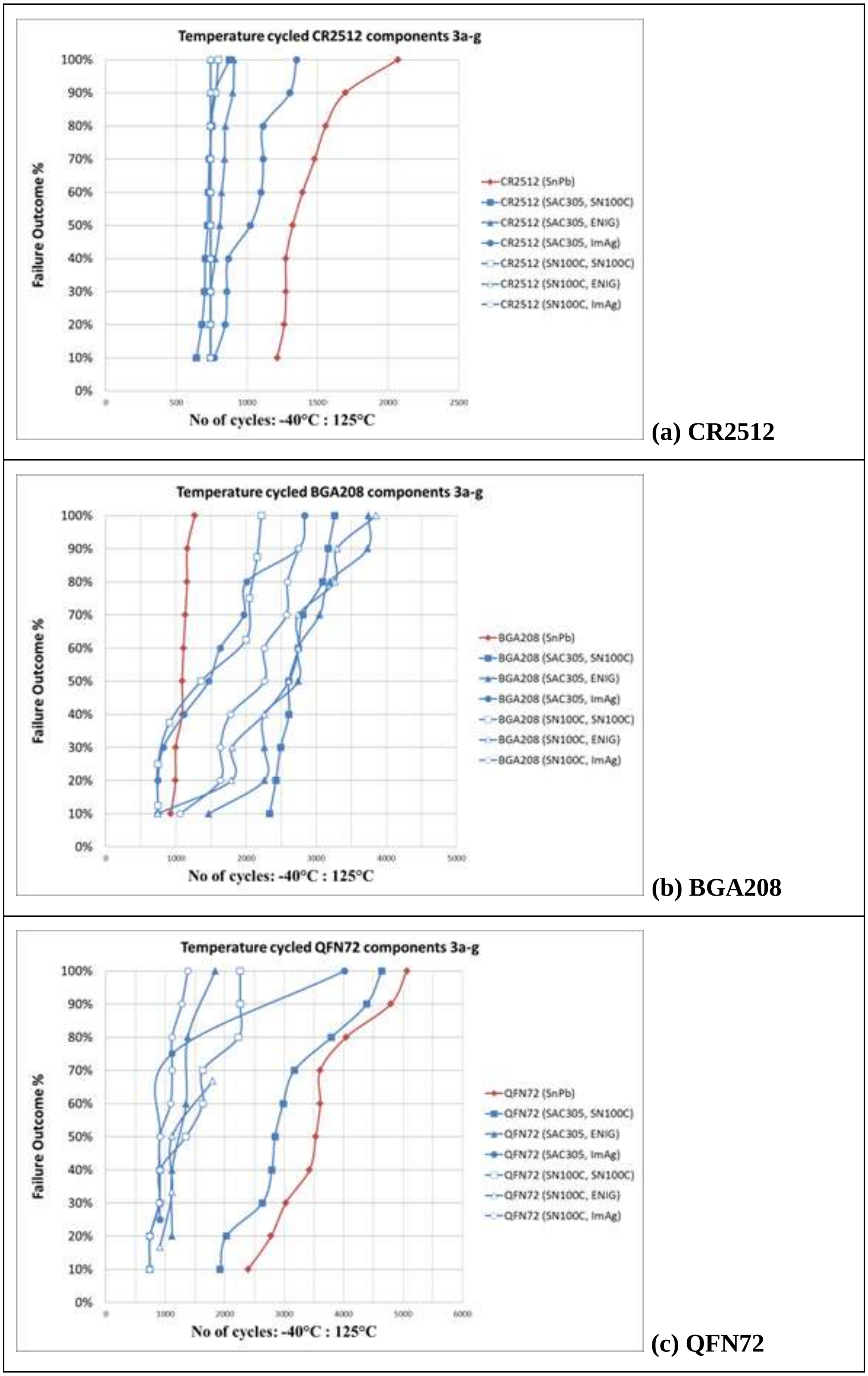
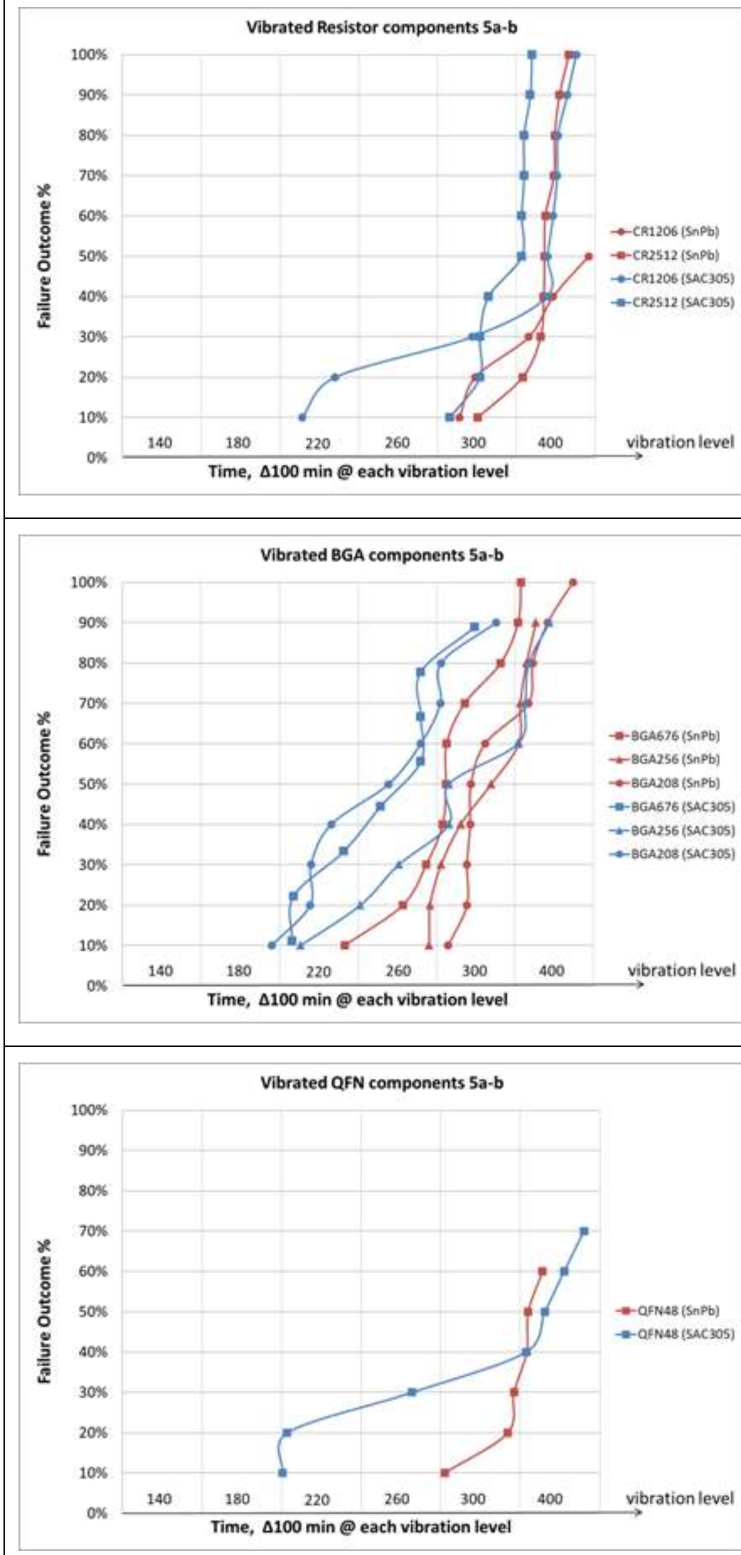


Figure 3. ***Failure outcome after temperature cycling of test vehicles with various components.***



(a) CR1206

(b) BGA208

(c) QFN48

Figure 4. Failure outcome after vibration testing of test vehicles with various components.

5.4 Prediction of service life

A fictitious product exposed to 365 cycles per year was used to evaluate the reliability of lead-free soldering. The temperature variations included a temperature interval ΔT of 20ºC for 50% of the cycles, 40°C for 27% of the cycles, 60°C for 16% of the cycles and 80°C for 6% of the cycles. The IPC classification for automotive electronics stipulates maximum 0.1% failure outcome as requirement for mounting in the passenger compartment which would correspond to cab mounting for heavy vehicles. For temperature cycling between -40°C and 125°C with 10 years required life time, the required number of cycles should be N(63%) > 1500 cycles and for 15 years life time N(63%) > 2250 cycles. For power train applications, the requirement is 2000 cycles without any failure or 2500 cycles with maximum 1% failure.

Large ceramic resistors (2512) could withstand N(63%) = 750 cycles for lead-free and about 1500 cycles for tin-lead. These components were hence far from the requirements for lead-free but fulfilled the requirement for tin-lead considering the fictitious product with 10 years required life in cab mounting. However, requirements for 15 years life time could not be fulfilled. Smaller ceramic resistors (1206) could fulfil the requirement with large margin both for lead-free and tin-lead.

BGA components with 1mm pitch in lead-free could withstand 3000 cycles without failure, hence these components should be able to use without risk even for more harsh service environments.

BGA208 components with 0.8mm pitch in lead-free could withstand the requirement of 2250 cycles for some combinations of lead-free solders and solder surfaces although without margin (N(63%) about 2700 cycles). With thicker PCBs, larger components, use of lacquer and possible also lower CTE of the moulding plastic, there is an impendent risk that the requirement will not be fulfilled. For two combinations of lead-free solders and solder surfaces, the requirement for power train mounting was not fulfilled.

For BGA components with pitch less than 0.8mm, there is an impendent risk that the requirement will not be fulfilled even for mounting in a passenger compartment, possibly with the exception of small components. For such components, it may become necessary to use underfil to reach sufficient service life.

BGA components with 0.8mm pitch in tin-lead could not fulfil the requirement of 1500 cycles (N(63%) = 1100-1300 cycles) and may therefore impose a large reliability risk. However, with use of older type of moulding plastics, it is assumed that the requirements would have been fulfilled.

QFN72 components could fulfil the requirement with good margin for both lead-free (N(63%) = 3000 cycles) and tin-lead (N(63%) = 3500 cycles) considering the test vehicles that were produced initially. The outcome was however deteriorated for components that were soldered in a later batch. The inferior result was most likely related to reduced solderability after storing. The solder surface of a QFN component is partly below the component and partly along the component side. The solder surface below the component is protected from oxidation using either tin or Ni/Pd/Au. However, the solder surface along the component side has no oxidation protection. The solderability of the bare Cu surface is rapidly deteriorated upon storage. This will result in impaired wetting of the solder surfaces along the component sides for the components that were soldered at a later occasion. This is a probable explanation to the reduced N(63%)- value. It is hence important to ensure sufficient wetting of the side solder surfaces of the QFN components to reach optimal reliability.

6. Delivery to FFI goals

The project has contributed to several of the FFI objectives, the most important are described below.

The project has established that deeper knowledge about critical failure mechanisms in relevant service environments will be crucial to ensure reliability during long-term use after the change-over to lead-free green products. Knowledge that can eliminate the use of lead is urgent from an environmental perspective and companies that can handle this change-over without compromising the product reliability will achieve competitive advantage.

The project has contributed to increased knowledge and awareness about what is needed to implement lead-free products for automotive applications. Utilization of the retrieved knowledge will support future jobs and production in Sweden.

National research and development efforts with focus on electronic hardware and reliability has been down prioritized during a number of years and several universities have discontinued with earlier activities. There is a large need to build knowledge within this field to support Swedish industry with implementation of lead-free products. The change-over to lead-free soldering occurs simultaneously with several other changes related to design and production of electronic hardware and measures to ensure reliability will be crucial for companies that manufacture and use electronic products with long expected life time and use in harsh environments.

The project has also strengthened the research environments within the research institutes, the research suppliers have been given the opportunity to increase the knowledge within the field of electronic hardware reliability. This knowledge can be used in the future by other companies that will face similar challenges. The development in the area is however rapid and it is important that the knowledge gained can be maintained and further developed. It is therefore of uttermost importance with continued national collaboration. The knowledge platform that has been developed within the project is also beneficial for future participation in European collaborative projects. It is important with enhanced European collaboration to meet the global competiveness.

The project consortium has provided a much appreciated possibility to collaborate between automotive producers/electronics purchasers, suppliers/electronics producers and research institutes. The project has also provided a unique possibility for cross industry collaboration between the automotive and the aerospace industry. It has been possible to share experiences and knowledge between these industry sectors that are facing similar challenges when new directives or lack of lead-containing components will require a change-over to green lead-free technology.

7. Dissemination and publications

7.1 Knowledge and results dissemination

The project result will be discussed and shared at internal workshops within the participating companies. Designers and quality engineers will have the possibility to share the results and to discuss how the new knowledge should be considered and used.

Expected European directives and lack of tin-lead components will increase the need for knowledge within this field. New test methodologies and way of working will be required to ensure reliability during long term use in harsh environments.

The project has provided possibilities for the research institutes to build increased knowledge within the field and this knowledge is expected to be spread to other companies with corresponding needs.

8. Conclusions and future research

The project has shown that the methodology common used today to ensure reliability during design, manufacturing and testing is not sufficient to ensure reliability after the change-over to lead-free soldering. It is urgent to implement test methodologies that are knowledge based and considers failure mechanisms that are occurring in relevant service environments.

The project has identified critical failure mechanisms and has also pointed out potential reliability problems for specific components when using lead-free solders and solder surfaces. Experimental results from temperature cycling and vibration testing have verified findings in the literature. Failure outcome during testing was monitored in-situ and causes of failure were analysed. The results were consistent and service life and causes of failure could clearly be related to specific component types and selection of solder/solder surfaces.

The change-over to lead-free soldering is occurring simultaneously with several other changes related to design and manufacturing of electronic products and the project has also identified other potential reliability problems that are not directly related to lead-free soldering. The project consortium with partners representing different parts of the value chain and different industrial sectors has been very valuable and has provided the possibility to illustrate problems and solutions using different perspectives.

Continued research should be focused on critical failure mechanisms for further components but should also consider other potential reliability risks that may rise when component manufacturers develop products with focus on functionality rather than long term reliability. Reliability should be considered already in the design stage and continued research should consider more knowledge based way of working to ensure robust and reliable electronic hardware for future products.

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