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A reliability assessment guide for the transition planning to lead-free electronics for companies whose products are RoHS exempted or excluded

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ABSTRACT

While a majority of electronic manufacturers have transitioned to lead-free materials and processes, both to comply with government legislation and to be compatible with the evolving supply-chain infrastructure, there are still many electronic manufacturers who are not using lead-free technologies, because they produce products that are either currently exempted or excluded from the government-imposed restrictions. Nevertheless, at some time, these manufacturers will need to have a lead-free transition plan, which includes compliance identification of the materials used, supplier compliance, process updates, and reliability assessment and qualification to the targeted application. This paper first briefly overviews the state of the knowledge as it relates to the reliability of lead-free solders. Then the paper provides a guide to help the planning team to assess the reliability issues needed for scheduling and resource identification to ensure a cost-effective and timely transition to lead-free products. The focus is on a risk matrix developed to help companies determine the general category of risk that they will encounter if they are currently exempt or excluded from making lead-free electronics.

1. Introduction

In 2002, the European Union (EU) passed the Waste Electrical & Electronic Equipment (WEEE) directive to mandate the reuse, recycling, and recovery of electrical and electronic equipment waste that was being disposed of in European landfills. The goal was to reduce the release of hazardous substances into the environment. The WEEE directive required manufacturers to register their products and implement a plan to recycle in each EU country, and manufacturers were required to provide refurbishment, treatment, and reuse guidelines for each WEEE-compliant product.

Ten categories of electrical and electronic equipment were covered by the WEEE directive, including household appliances, information technology and telecommunications equipment, lighting equipment, electrical and electronic tools (with the exception of large-scale stationary industrial tools), toys, leisure and sports equipment, medical devices (with the exception of all implanted and infected products), monitoring and control instruments, and automatic dispensers. The WEEE directive was applicable to all of the products falling into the ten categories placed in the market after August 13, 2005.

Realizing that controlling the waste stream alone would not solve the issues associated with hazardous substances, efforts were made to restrict hazardous substances at their origins [1]. As a result, in 2003, the Restriction of Hazardous Substances (RoHS) directive limited the use of certain hazardous substances in electrical and electronic equipment in EU member states and provided a mechanism for restricting additional substances in the future [2]. The RoHS directive (2002/95/EC) became effective on July 1, 2006, and was applicable to the ten categories of products listed in the WEEE directive, as well as to electric light bulbs and luminaires used in households.

The RoHS directive was updated in July 2011 as RoHS 2 [3], and although it did not restrict any additional materials, the directive provided deadlines for some exempted applications unless a technical reason was provided for continuing the exemption. In particular, the RoHS 2 directive required medical devices and monitoring and control instruments to comply with current RoHS restrictions by July 2014 and industrial control and monitoring instruments to comply by July 2017. For all other equipment, unless explicitly excluded, compliance is required by July 2019. The electrical and electronic equipment explicitly excluded were equipment used in military and space applications, large-scale stationary industrial tools, large-scale fixed installations, implantable medical devices, transportation applications (except for electric two-wheel vehicles), non-road mobile machinery, photovoltaic panels designed for permanent use, and equipment designed solely for the purpose of research and development [4]. The use of high melting temperature-type solders (i.e., lead-based alloys containing 85% or more lead by weight) remained exempt in the RoHS 2 directive for all applications. However, since all exemptions are bound to expire at

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some point in the near future, the electronics industry will need to continually evaluate the options if the exemptions are to expire.

With consumer (including computer and smart phone) electronics driving the trends in technology, the majority of electronic component manufacturers have already transitioned to the use of lead-free materials [5]. New electronic device architectures and technologies are not being developed in lead-based packaging. This trend has resulted in the decreased availability of tin–lead-based components, surface finishes and interconnection materials.

The majority of electronics manufacturers have now transitioned to lead-free materials and processes, both to comply with government legislation and to be compatible with the supply-chain infrastructure [6–8]. On the other hand, electronic manufacturers associated with the excluded and exempted products have generally attempted to maintain lead-based parts and assembly processes due to long-term reliability concerns with lead-free parts and assemblies. However, even some of these manufacturers have been investigating, and in some cases using, lead-free parts because they are the only parts that are affordable and available on the market. For example, it is nearly impossible to purchase high-density BGA packages in leaded versions [5]. As a result, manufacturers using tin–lead solder face the decision of assembling a lead-free BGA with tin–lead solder or replacing the lead-free solder balls on the BGA with tin–lead solder balls. In the case of re-balling, process control and material knowledge are necessary to mitigate potential damage to the part. In the case of mixed solder attachment, process control and thermal loading must be considered in order to avoid defective attachments. This situation has created a general nightmare for the selection of parts, the assembly processes, the repair and maintenance of assemblies, and obsolescence management. Companies that have been exempted or excluded by the environmental legislation have been forced to make last-time buys and store spares or to use re-worked lead-free components. With potential reliability concerns from such re-worked assemblies as well as the risks associated with the inclusion of counterfeit components and the shrinking manufacturing base, these companies are now being compelled to evaluate the transition to lead-free materials.

This paper overviews the key reliability risks in lead-free electronics. The intent is to address all the key failure mechanisms of concern, but not to be an extensive analysis of any particular failure mechanism; the interested reader is referred instead to the key references given at the end of this paper. Next, the paper presents the concept of a risk matrix that was developed to help companies determine the general level of risk that they will encounter if they are currently exempt or excluded from making lead-free electronics. Finally, some real product examples are given.

2. Reliability risks in lead-free electronics

When RoHS was first legislated, the concern was that no drop-in replacement for eutectic tin–lead solder had been identified. Further, the terminal finishes of package electronic devices and printed circuit boards were not optimized for any particular lead-free solder. However, the commercial electronics industry was prepared for legislation and had researched and settled on tin–silver–copper (SAC) solder, as well as various finishes (plating) for the printed circuit boards and for the electronic device terminals (leads). Their findings were that lead-free assemblies could be made to have as good reliability as the preceding lead-based assemblies [9,10].

This section briefly overviews the various failure mechanisms of potential concern with lead-free solders. The purpose is to show that these concerns have been adequately addressed in consumer electronics, computers, smart phones and other products that have been legislatively required to be lead-free, and point out the possible remaining concerns for exempted and excluded products.

2.1. Solder interconnect reliability

The conversion to lead-free materials in electronics has focused primarily on the solder material. After extensive examination of available solder materials, the tin–silver–copper alloy has emerged as the primary replacement for tin–lead solder. However, the specific composition of the tin–silver–copper alloy has been a subject of continued refinement. Early research focused on the near-eutectic Sn4.0–3.8%Ag0.7–0.5%Cu. Over time, the tin–silver–copper composition shifted to Sn3.0%Ag0.5%Cu, commonly referred to as SAC305. While other lead-free solder materials, such as Sn–Cu and Sn–Ag, have found some use, the SAC solder remains the most widely used. According to Kester [24], 68% of SMT assemblers are using tin–silver–copper solder.

With regard to SAC305 solder, temperature cycling durability has been found to be better than tin–lead solder interconnects under a variety of conditions. However, there are particular parts and temperature conditions at which tin–lead solder interconnects still outperform SAC305. Fortunately, design-for-reliability models for SAC solder are available to estimate the useful life [25].

Under vibration loading conditions, the life expectancy of the interconnection between a packaged electronic device and the printed wiring board to which it is mounted is strongly dependent on the interconnection format, the position of the part on the printed circuit board, the mounting conditions of the printed wiring board, and the loading conditions. Under random vibration loading with stepped increases of strain levels, SAC solder interconnections at the same location and under the same loading conditions exhibited earlier failure than SnPb solder attachments [26]. In a study that combined random test data with harmonic test data, Yhou and Dasgupta [27] determined that SAC solder may be more durable than SnPb solder at low cycle fatigue (<1 million cycles). For leadless surface mount resistors subjected to random vibration with stepped increases in strain levels, test data indicated that SAC-soldered parts experienced failures sooner than tin–lead soldered parts, but the differences in mean cycles to failure were statistically insignificant [28]. Further, testing of the mechanical cycling durability of BGA and leadless chip resistor attached with SAC and tin–lead solder, including ultra-low cycle (<100), low cycle (<10,000), and high cycle (>100,000), as a function of board strain, determined that at lower strain levels (e.g. <2000 microstrain), the SAC305 and tin–lead solder interconnects exhibit approximately the same durability [29]. Testing of BGA package format parts and chip resistor parts revealed separation of tin–lead and SAC305 solder attachment at low cycle, high strain level conditions (i.e., shock loading). Under high strain level (>4000 microstrain) loading conditions, the tin–lead solder attachments were found to withstand high strain events compared to SAC305 solder [29]. Additional harmonic testing at board half-cycle strain levels of 300 microstrain has found that SAC solder attachments formed on ENEPIG-finished board terminations to be superior to SnPb solder attachments, while the reverse was observed for solder attachments formed on immersion-silver-finished board terminations [30]. Overall, the findings indicate that SAC attachments may experience lower lifetime under vibration loading conditions, particularly if high strain range (>4000 microstrain) content is included.

SAC305 solder interconnects have been found to have lower durability than tin–lead when it comes to drop/shock reliability, especially for area array packages. This reduced durability has prompted a search for solder alloys used in BGA construction that will provide better drop/shock performance. The drop–shock results have led to the examination of lower silver content tin–silver–copper alloys with the possible addition of other elements such as manganese and titanium [31].

For most package types, SAC solders outperformed SnPb solders when the peak cyclic temperature was below 125 °C. The effect of dwell on all solders, including SnPb, is more significant at lower cyclic mean temperatures. The fatigue life of SAC solders became closer to that of SnPb solder as the temperature cyclic mean temperature increased. Temperature cycle fatigue life can be simulated and