Converting to Lead-Free Solders: An Automotive Industry Perspective

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The solder tests currently used in defining solder alloy properties are not sufficient for selecting interconnect materials for improved reliability and reduced cost in automotive electronic applications. A "preventive" design approach based upon more accurate models of failure mechanisms and life prediction than are currently available will be required in order to assess solder alloys and to determine whether lead-free solders will provide improved reliability and lower-cost manufacturing options when compared to the lead-based solders currently used.

INTRODUCTION

The design process, as it is currently practiced, is being broadened to include consideration of the full product life cycle (i.e., conception through recycling at the end of the product's useful life). Within this framework, an important issue emerging for the automotive industry is the use of lead-containing alloys in the manufacture of electronics. It is not only the manufacturing that is of concern, but also the possibility of lead contamination of ground water when electronic components are discarded in landfills. Does the search for a replacement for lead-alloy solders offer the industry an opportunity to improve electronic manufacturability and reliability while reducing costs? If the design process is improved, the answer will be "Yes."

New automotive electronic products are being employed in an ever-increasing number of areas to meet the customer demand for comfort, safety, economy, and functionality. Electronic control and sensor devices play a central role in many of the improvements in power-train efficiency and performance, as well as in reducing emissions, and reliability of the devices is a critical issue. In the under-hood environment of the automobile, harsh thermal and chemical conditions require sophisticated design methods, materials, and tools to provide reliable, cost-effective packaging.

To assure reliability in highly dense packaging structures composed of ceramic, polymeric, and metallic materials in both bulk and layered composite forms, an interdisciplinary systems approach is needed that involves the engineering disciplines and the sciences of mechanics, materials, and manufacturing. Models that accurately describe a material system's response to in-service thermal and chemical environments must be developed and validated in order to anticipate failure modes and quantitatively predict product life for particular failure mechanisms. Such an approach would provide the basis for selecting lead-free solder alloys capable of providing improved interconnect reliability. Probabilistic models offer an approach for including the reliability effects related to manufacturing variability and a method for assuring manufacturability with lead-free solders.

ELECTRONIC PACKAGING

Package systems play an essential role in determining the performance and reliability of electronic devices in under-hood applications. At a functional level, the package provides for electrical interconnection, thermal management, corrosion protection, and mechanical support for the integrated circuit chips and other electronic circuit components. At the various packaging levels, there are chip carriers, substrates, circuit boards, electrical connectors, cables, and frame, and all must be interconnected. This complex task requires the use of dissimilar materials (e.g., metals, ceramics, and polymers), which complicates device design, manufacture, and reliability.

Harsh environments (see Table I) ensure that expansion mismatch will present a severe test of device reliability because of the stresses imposed on joint materials as the package undergoes temperature changes. The wide variation in expansion coefficients between the materials (see Table II) can result in large stresses in critical connection areas unless packaging is carefully designed.

Functional integration and miniaturization of electronic modules is further exacerbating the problems of ensuring reliability. Surface-mounting technology has been developing to meet the packaging density challenge with leaded and leadless interconnects, which include such methods as flip-chip and tab mounting as special cases. Solder-joint durability is of particular concern because of the susceptibility of solder to low-cycle thermal fatigue.

PACKAGING INTERCONNECTS

Because of the large expansion mismatch possible in packaging structures and the harsh automotive thermal envi-
environments, the interconnect design process must be made as reliable as possible. Researchers at Ford Motor Company have been attempting to develop a methodology for packaging design referred to as a design-for-reliability approach. The methodology provides a design process for achieving high-reliability products at lowest cost.

In simplest terms, design-for-reliability emphasizes the need to consider products as material systems that must be thoroughly understood early in the design process. Delineating critical failure modes and understanding their root causes is the central focus; this information is linked to the design through its use in estimating product life. The traditional build, test, and fix design approach is inefficient and of marginal value as a basis for guiding the design process to improve reliability at lowest cost. Figure 1 illustrates the contrasts between the outmoded "detection" (build-and-fix) approach and the preferred "prevention" approach.

**Solder as an Interconnect Material**

While a number of interconnect methods such as wire bonding, laser welding, and adhesive joining are widely used in the packaging of automotive electronics, soldering is by far the most economical and is the process of choice in the industry. Hundreds of joints are formed on a single complex printed wiring board in a matter of seconds during a reflow or wave-soldering operation.

Generally, the solder joint must carry the responsibility of providing both an electrical connection and mechanical support; therefore, one might think solder to be an unlikely choice. The commonly used 63Sn-37Pb eutectic alloy has a melting temperature of only 183°C, and it has been used for applications in packages where the operating temperatures can reach 125°C. This represents a high homologous temperature, which is not a criterion generally used in selecting a structural material where strength is desirable.

Figure 2 illustrates the significant reduction in strength that occurs with increasing temperature for tin and two common solder alloys. Low-melting interconnect alloys are chosen principally to protect the surface-mount devices from thermally induced damage during manufacturing.

Whether solder represents the optimum interconnect material for the future is extremely important. In a "detection" design environment, one takes a wait-and-see attitude before changing alloys. With the "prevention" approach one attempts to select materials based on a reliability criterion before the prototyping stage is reached.

**Solder Interconnect Failure Modes**

As an electronic module is exposed to a varying thermal environment in service, the packaging interconnects are subjected to thermal expansion mismatch loads created by the various materials used. Several common joint designs are illustrated in Figure 3. Since the solder is typically the mechanically weakest material forming the joint, it experiences most of the plastic deformation. If severe enough, this deformation will cause a fatigue-type failure in a relatively low number of thermal cycles.

Consider the task of modeling the joint-deformation process in a particular packaging structure. In spite of the large number of mechanistic studies of low-cycle solder fatigue, no first-principles model has yet been developed that character-

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**RELIABILITY**

**(Design Information Content)**

- **Detection Design Mode**
  - Past Performance Analysis
  - Prototype Build
  - Accelerated Testing
  - Iterate

- **Prevention Design Mode**
  - Failure Mode Analysis
  - Root Cause Modeling
  - Life Prediction Modeling
  - Model Validation Testing
  - Computer Design Analysis
  - Prototype Build
  - Accelerated Valid Testing

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**Figure 1.** Design methodologies for achieving product reliability.

**Figure 2.** The temperature variation of tensile strength for near-eutectic and high-lead solder alloys.

**Figure 3.** Common surface-mount interconnect designs. (a) Flip-chip bump structure. (b) Pin through hole. (c) Leaded and leadless surface-mount technologies.