SOLDER JOINT RELIABILITY

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Abstract

The role of solder in electronic packages has expanded. In advanced designs, solder is an electrical inter-connect, a mechanical bond, and must often serve as a thermal conduit to remove heat from joined devices. Additionally, interconnects become more critical as die size, chip-carrier size, and number of inputs/ outputs (I/Os) increase, while solder joint size and cost decreases. This paper discusses reliability of solder interconnects for electronic packages and describe the methodologies used to prediction reliability. The specific reliability issues discussed will be thermomechanical stress (fatigue), creep behaviour, and interfacial intermetallics aging.

Key words

solder, reliability, intermetallic, aging, fatigue behaviour, creep behaviour

Introduction

The basic requirement of solder interconnects is to form an electrical and mechanical connection between package elements that retains integrity through subsequent manufacturing processes and service conditions. Solder joints are also required to have the capacity to dissipate strains generated as a result of coefficient of thermal expansion mismatches under service conditions over the lifetime of the assembly. Solder joint reliability is the ability of the interconnect to retain functionality under use environments. As the number of joints increase, and their size decreases, the reliability of solder joints becomes an issue because they are more difficult to manufacture and functionality requirements become stricter [1].

After assembly, solder joints must retain integrity when exposed to a variety of application conditions that include mechanical and environmental stress, either individually or in combination.

Vibration

This is caused by rapid, relatively small displacements in reversing directions that can cause fatigue failures. Vibration is a more serious issue with heavier objects and has not typically been a problem with electronic component interconnections. However, it must be considered for transportation applications such as avionics and automobiles.

Mechanical Shock

Shock can occur in an electronic package if an assembly is mishandled. A shock environment involves short-term exposure to high loads and is worse for heavier objects. For area-array solder joints, shock can be a problem for die-level interconnects if the die is directly attached to a heat sink and package-level interconnects in high-mass packages.

Thermomechanical Fatigue

Electronic packages consist of a variety of materials that have different coefficients of thermal expansion (CTE). In service, packages are often exposed to thermal fluctuations owing to internal heating (Joule heating of the device) or ambient temperature changes. Solder interconnects experience cyclical strains resulting from the CTE mismatch between joined components when the ambient temperature changes or the machine goes through on/off cycles.

Thermal Aging

In service, electronic packages can be exposed to high temperature caused by the ambient temperature (under the hood of automobiles) or dissipated heat from a packaged device. The micro-structure of solder interconnections can evolve to a coarsened structure that is weaker and inter-facial reactions that form brittle intermetallics are accelerated.

Humidity

The presence of water and ionic species can result in corrosion if an electrical bias exists resulting in electrical opens or electrical shorts if the corrosion products are electrically conducive.

Solder interconnects must retain integrity throughout their service lifetime. The most prevalent long-term reliability issues that can result in interconnect failure are thermomechanical fatigue and thermal aging. Metallurgical factors that affect characteristics such as bond formation, creep, and fatigue behavior must be understood. The following is an overview of factors that influence the reliability of solder joints [3,5].

Creep Behavior

Time-dependent deformation (creep) occurs when a constant load, or strain, is imposed on a material and the material deforms over time to reduce the load. For solder interconnects, creep mostly occurs when the assembly undergoes a change in temperature (i.e., ambient temperature changes). The strain arises owing to CTE mismatches between joined materials in electronic assemblies that expand and contract to different lengths as the temperature changes (e.g., the CTE of silicon is 3 ppm°C^{-1}, an Al_20_3 chip-carrier is 6 ppm°C^{-1}, and an organic chip-carrier is about 17 ppm°C^{-1}). The shear strain imposed on the solder joints follows the relationship

$$\Delta\gamma = \Delta\alpha \Delta T \frac{a}{h}, \quad (1)$$

where $\Delta\gamma$ is the shear strain imposed, $\Delta\alpha$ is the difference in coefficient of expansion between the joined materials, ΔT is the temperature change, a is the distance from the neutral expansion point of the joined materials, and h is the thickness of the interconnect.

Creep behavior of solder materials is very important to the mechanical reliability of interconnects. Solders undergo creep to relax imposed stresses. Creep damage accumulates in the solder rather than in the more brittle components to which it is attached. Further-more, the damage mechanism during thermomechanical fatigue is similar to that during creep deformation.

The damage mechanisms during creep occur in the interconnects or in the joined components if the strain is not accommodated in the solder. Typically, if the solder cannot accommodate the creep damage, the joined components must deform or fracture. Damage in the solder can range from a change in joint shape at may create stress concentrations in a joint), to microstructural evolution through grain and phase coarsening (that lowers joint strength), to void or crack formation and propagation to failure. All joints change shape to some extent and multiphase solders with lamellar structures (eutectic Sn–Pb, Sn–Ag, and their alloys) undergo microstructural evolution and coarsening.

Experimental creep data can be used to predict the behavior of solder interconnects. A constitutive relationship derived from creep tests quantitatively models and predicts joint behavior through finite element simulations. The power-law creep equation is typically used to describe the behavior of solders:

$$\dot{\varepsilon}_{\min} = A(\sigma_c)^n \exp\left(-\frac{Q}{RT}\right), \quad (2)$$

where ε_{min} is the true minimum strain rate, A constant, σ_c the critical flow stress (MPa), n the stress exponent (a constant), Q the creep activation energy (Jmol^{-1}), R the universal gas constant (8.314 Jmol^{-1}K^{-1}), and T the absolute temperature (K). Creep data are derived from tests that impose a constant stress imposed on a solder joint and the resultant strain is measured [3,4].

Thermomechanical Fatigue Behavior

Thermomechanical fatigue occurs when materials with different CTEs are joined and used in an environment that experiences cyclic temperature fluctuations resulting in imposed cycling strain. Thermomechanical fatigue is a major deformation mechanism concerning solder interconnects in electronic packages. Even small temperature fluctuations can have a large effect, depending on the joint thickness and CTE difference of the joined materials. After a critical number of thermal excursions, such as machine on/off cycles, solder joints experience fatigue failure. The type and magnitude of strains in solder joints under conditions of thermomechanical fatigue are often quite complex. For surface mount applications, the strain is nominally in shear. However, tensile and mixed-mode strains can occur owing to bending of the chip carrier or board.

The combination of strain and temperature during thermomechanical fatigue has a large effect on the microstructure, and microstructural evolution of eutectic Sn-Pb solder joints. The microstructural evolution of 60Sn-40Pb solder as a function of the number of thermal cycles (- 55 °C to 125°C) is shown in Fig. 1. The microstructure evolves through deformation that concentrates at the colony boundaries closely parallel to the direction of imposed shear strain, causing the cells to slide or rotate relative to one another. The structure within the cell boundaries becomes slightly coarsened relative to the remaining solder joint micro-structure, and thus is the "weak link" of the joint. Damage (in the form of defects or dislocations) is created at the cell boundaries at the low-temperature portion of a thermal cycle. As the temperature rises, the deformation is annealed by stress-assisted diffusion where material diffuses to regions of high stress. This results in coarsening of the tin- and lead-rich grains and phases in colony boundaries. The heterogeneously coarsened colony boundaries are weaker than the rest of the joint and any further deformation concentrates in the coarsened regions resulting in further coarsening. Failure eventually occurs owing to cracks that form in the coarsened regions of a joint as shown in Fig. 2. The first indications of impending failure are associated with cracking of coarsened tin-rich grains in the heterogeneous region whose initial as solidified grain size is in the submicrometer range. When cracks initiate during thermomechanical fatigue, the tin grain size grows to about 5-10µm. Failure occurs when grains can no longer slide and rotate to accommodate the imposed strain resulting in intergranular separation [3].

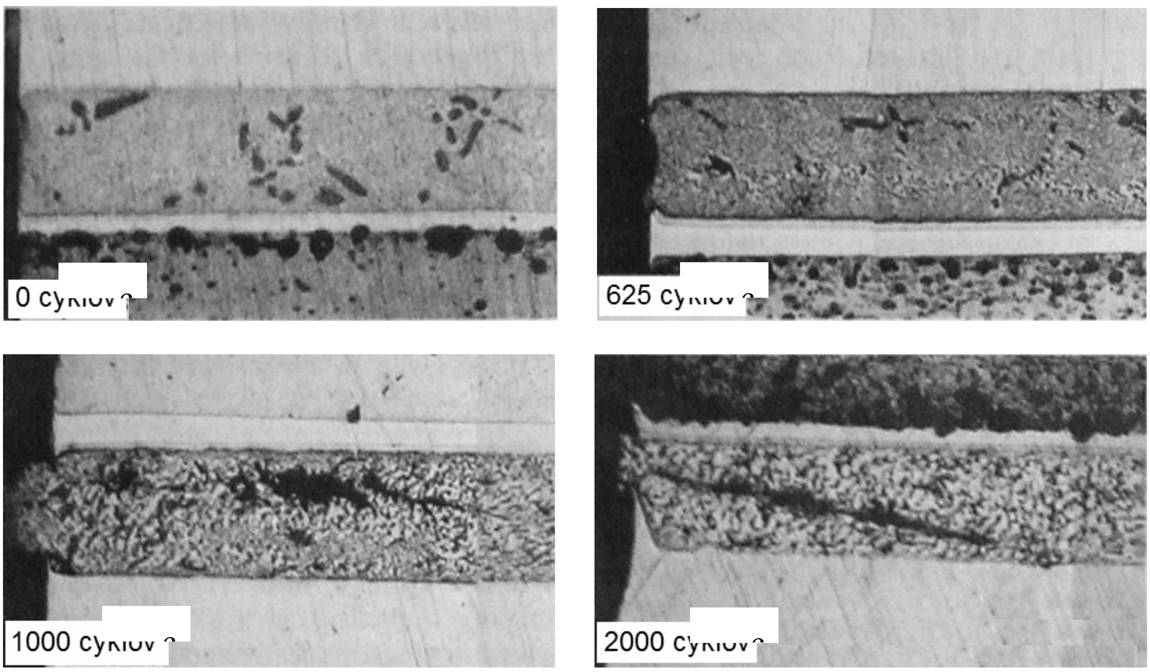

Fig. 1 *Heterogeneous coarsening of SnPb40 solder after thermomtchanical fatigue [3]*

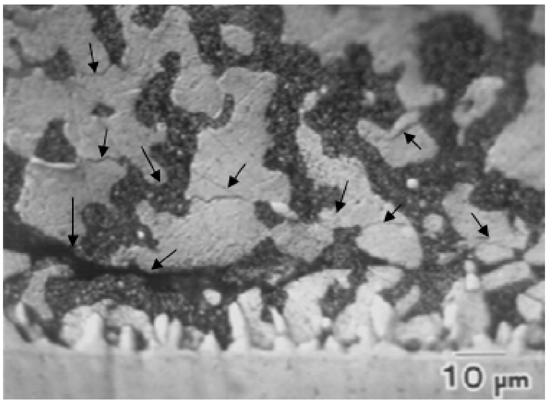

Fig. 2 *Cracks propagate through the Sn-rich phase at Sn-Sn grain boundaries after thermomechanical fatigue [3]*

Other solder alloys, such as the lead-free Sn-3.5Ag eutectic-based solders, experience thermomechanical fatigue damage and failure at tin grain boundaries (Fig.3). The microstructural evolution in these alloys tends to be phase coarsening with minimal grain size coarsening.

Sn-Ag-X alloys tend to have longer thermechanical fatigue lifetimes than near-eutectic Sn-Pb solders [5].

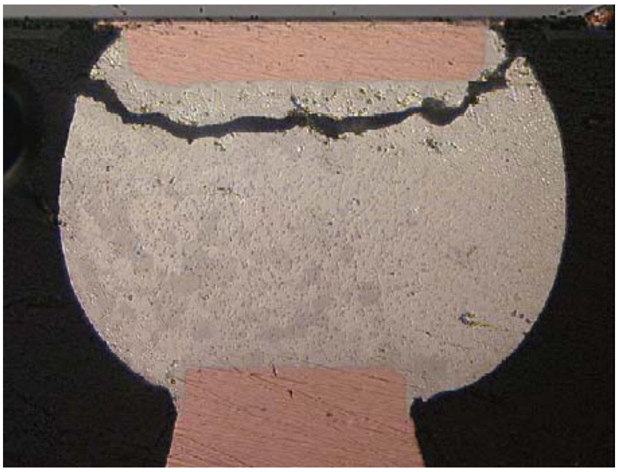

Fig. 3 *Optical micrograph of a failed Sn-3,5Ag solder joint after experiencing thermomechanical fatigue [5]*

Aging of Interfacial Intermetallics

Intermetallic compounds form between pad metallization and the active components of the molten solder (typically tin). For a copper metallization, the tin reacts to form Cu_3Sn and Cu_6Sn_5 intermetallics (Fig.4). After solidification, the intermetallic compounds continue to grow by solid-state diffusion. Over long periods of time, the intermetallic layers can grow to significant thicknesses (> 20µm) and the solder/intermetallic interface may constitute easy sites for crack initiation and propagation. Excessive growth also consumes the base metal, or finish, that can result in the loss of adhesion to the underlying metal that is not solder wettable or create a plane of weakness owing to the stress generated from an intermetallic layer that is too thick. The metallized pad thickness generally must be greater than that consumed by the solder.

The transformation of solder-wettable coatings into intermetallics by solid-state reactions can also result in excessive intermetallic growth that degrades mechanical properties. The interfacial intermetallics are brittle and may fracture when strain is imposed, especially if the strain is tensile in nature. Solder joint interfacial intermetallics are brittle because they typically have complex crystal structures with few crystallographic planes available to accommodate stress by strain relief, i.e., plastic deformation via a slip mechanism. The failures are characteristically brittle and occur through the intermetallic or at the intermetallic/solder interface under low-load conditions [5].

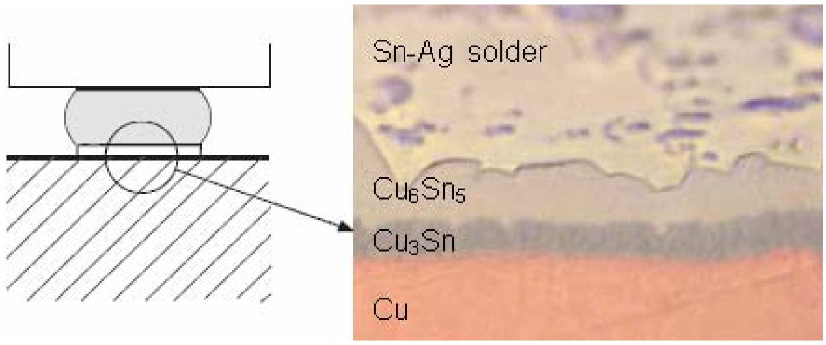

Fig. 4 *Structure of BGA soldered joint with intermetallic compounds and its details for SnAg solder[5]*

Reliability Prediction Methodologies

The lifetime prediction of solder joints for electronic packaging applications is a quantitative means of predicting reliability. A number of methodologies have been proposed to predict the reliability of interconnects under environments where failures typically can occur: thermal aging and thermomechanical fatigue.

In thermal aging, intermetallic growth is a concern for both the formation of a thick brittle intermetallic layer and for the consumption of the solder-wettable layer. Intermetallic compound growth rate in the solid state can be predicted using an Arrhenius relationship as a function of time and temperature:

$$x(t,T) = x_0 + At_n \exp\left(-\frac{Q}{RT}\right) , \qquad (3)$$

where x is the total intermetallic thickness (mm), t is the time (s), T is the temperature (K), x_0 is the thickness of the intermetallic in the as-soldered condition (at t= 0) (mm), A $(mm\ s^{-1})^n$ and n (unitless) are constants, R is the universal gas constant (1.98 cal mol^{-1} K^{-1}), and Q is the apparent activation energy for a particular growth process (cal). A, n, and Q are constants that can be obtained by means of multivariable linear regression analysis of quantitative intermetallic growth data. This equation predicts intermetallic growth but not reliability when mechanical strains are imposed. Materials-based finite element simulations are useful for predicting the ability of a given intermetallic layer to survive a given mechanical environment.

Many methodologies for predicting solder joint lifetime under conditions of low-cycle thermomechanical fatigue have been proposed. Low-cycle fatigue represents cycling in a range where some plasticity is encountered and is typical for thermomechanical fatigue. Most methodologies are empirical in nature and the complexity of the methodology depends on the desired accuracy of the results. In the empirical methods, test sample data (or field failure data) are collected and failure models developed. These models typically are a mathematical fit through the data. A variation of the Coffin–Manson relationship is often used as the basis of these models:

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{1/c}, \quad (4)$$

where Nf is the number of cycles to failure, $\Delta\gamma$ is the total shear strain, and ε_f and c are empirical constants.

For solder joints, tests can be performed isothermally at a variety of temperatures at strain levels calculated from a given thermal cycle range (Eqn. (1)) that are mechanically imposed on the joints until failure occurs. The strain levels in the solder joint can also be determined computationally using finite element analysis. Thermal cycling tests are more complicated and difficult to perform but provide more realistic test conditions. These failure models are then applied to similar geometries under different loading conditions to "predict" reliability. This methodology requires substantial test data that correlate very well with actual use conditions.

One of the common difficulties with experimentally determining reliability is that the tests must be performed under accelerated conditions by increasing the strain range, increasing the temperature range, or increasing the strain rate, all of which decrease the time to failure. Unfortunately, each of these conditions can also change the deformation mechanism in the solder and invalidate the results. Care must be taken to ensure that the damage, and failure, mechanisms are the same for the accelerated tests as for the actual use conditions. Additionally, the microstructure of the solder changes depending on the strain/temperature environment (as shown in Fig. 2) that makes an extrapolation from one set of test conditions to field use complicated. The environment (strain and temperature history) along with the microstructure (and its evolution) and interconnect mechanical properties must be fully understood to predict solder joint reliability [2, 3, 4].

Conclusion

Solder interconnect reliability is the ability of a solder joint to retain full functionality in a use environment. The most insidious environments for solder degradation are high-temperature aging and thermomechanical fatigue because solders are microstructurally unstable and evolve with strain, temperature, and time. Solder joints experience time-dependent deformation, creep, owing to the materials with different CTEs in the package imposing strain on the joints when the temperature changes. Empirical equations can be used to predict creep behavior. Aging of interconnects results in growth of the brittle intermetallic layer. The effect of this growth on the reliability of the interconnect can be predicted using empirical relationships and materials-based finite element modeling. Solder experience failures owing to thermomechanical fatigue, a combination of temperature and strain cycling. Failures are often preceded by microstructural evolution that must be understood to predict reliability using empirical methods.

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