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Predicted Low-Cycle-Fatigue Lifetime of Solder Joint Interconnections: Application of Hall's Approach and Boltzmann-Arrhenius-Zhurkov (Baz) Model

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Abstract

A predictive model is suggested for the evaluation of the low-cycle-fatigue lifetime of a solder joint interconnection in an avionic IC package subjected to temperature cycling and experiencing low cycle fatigue conditions. The model is based on two significant findings in the field of electronic materials reliability. The first one is Hall's plastic strain energy approach suggested about forty years ago. According to this approach, the experimentally obtained area of the hysteresis loop of a single temperature cycle is viewed as the relevant characteristic of the irreversible degradation of the solder material. The second finding, suggested about a decade ago, has to do with the probabilistic design for reliability (PDfR) concept and its physically meaningful, highly focused and highly cost-effective failure-oriented-accelerated-testing (FOAT) designed and conducted for a new electronic packaging technology in accordance with an appropriate constituent equation. Multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) equation is used here in this capacity: It enables predicting the fatigue lifetime of the interconnection in the field condition from the FOAT data. The general concepts are illustrated by a numerical example.

Introduction

Although there are realistic ways to avoid inelastic strains in solder joint interconnections of IC packages or at least to determine and minimize the sizes of such strains [1], it is still more common than not that inelastic strains, leading to low-cycle fatigue, still take place in the solder material during accelerated testing and in actual field conditions (see, e.g., [2,3]. The objective of this analysis is to suggest a simple and physically meaningful methodology for the prediction of the lifetime of the solder material experiencing low cycle fatigue during temperature cycling. The methodology is based on two findings in the field in question: Hall's plastic strain energy approach suggested about forty years ago [4] and the author's probabilistic design for reliability (PDfR) approach suggested about a decade ago [5-9].

According to Hall's approach, the area of the hysteresis loop of a single cycle is viewed as the relevant characteristic of the irreversible degradation of the solder material. This area should be determined experimentally during specially designed and conducted accelerated tests. Hall considered interconnections between ceramic chip carriers/packages and printed circuit boards. The typical failure modes indicated by Hall were cracks in the solder materials as the consequence of that, electrical failures ("opens"). Being an outstanding experimentalist, Hall measured, using strain gages, the in-plane and bending deformations of the ceramic chip carriers (CCCs) and the printed circuit boards (PCBs) and based on these measurements, calculated the forces and moments experienced by the solder joints. It has been found that, for the considered materials and structures, "most of the expansion mismatch is accommodated by 'bi-metallic strip' type bending of the PCB and the CCC" and that "the change in bending during a temperature change from -25 °C to + 35 °C is consistent with the classical Timoshenko's [10] bi-metallic strip equation, given material properties from the literature" and that "above room temperature most of the mismatch is accommodated by shear in the solder". The important finding in Hall's investigations is that "upon repeated temperature cycling, there is a repeatable stress-strain hysteresis, which is attributed to plastic deformations in the solder". In Hall's experiments the strain gages were placed on both sides of

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the CCC (package). The strains were measured in the middle of the assembly, and it was assumed that they are "isotropic and uniform" in the plane, which is certainly not the case in actual assemblies. Hall emphasizes that "further work needs to be done to measure the directional dependence of the strain for the case of thermal chamber cycling". Another important simplification in Hall's experiments was the consideration of a "model with axial symmetry". "This assumes that the solder posts can be treated as if they were in a circular array and thus all equivalent". There were also several other simplifying and even disputable assumptions. It is noteworthy in this connection that the strength and the novelty of Hall's work is in the experimental part of his effort. The strains were measured as functions of temperature using commercial metal foil strain gages. Hall concludes that plots of the thermally induced force vs. displacement "can be used to yield the plastic strain energy dissipated per cycle in the solder" and that "this energy can be used to quantify micro-structural damage and eventually to predict lifetimes in thermal chamber cycling". It is this recommendation that is implemented in our analysis.

The second, the author's, finding suggests that, when a new soldering technology is considered, failure-oriented-accelerated-testing (FOAT) [7,8] should be designed and conducted in accordance with an appropriate multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) equation [8,9] that enables predicting the low-cycle fatigue lifetime in the field from the FOAT data.

Analysis

Using the BAZ model, the probability of non-failure of a solder joint interconnection experiencing inelastic strains during temperature cycling can be sought as

$$P = \exp\left[-\gamma R t \exp\left(-\frac{U_0 - nW}{kT}\right)\right] \quad (1)$$

Here $U_0, eV,$ is the activation energy and is the characteristic of the solder material's propensity to fracture, $W, eV,$ is the damage caused by a single temperature cycle and measured, in accordance with Hall's concept, by the hysteresis loop area of a single temperature cycle for the strain of interest, T, K is the absolute temperature (say, the cycle's mean temperature), n is the number of cycles, $k = 8.6173x10^{-5} eV/K$ is Boltzmann's constant, t, s, is time, $R, \Omega,$ is the measured (monitored) electrical resistance at the joint location, and γ is the sensitivity factor for the resistance. The above equation makes physical sense. Indeed, the probability P of non-failure is zero at the initial moment of time $t = 0$ and when the electrical resistance R of the joint material is zero is one; this probability decreases with time, because of material aging and structural degradation; this probability is lower for higher electrical resistance (a resistance as high as, say, 450Ω, can be viewed as an indication of an irreversible mechanical failure of the material); materials with higher activation energy U_0 have a lower probability of damage the increase in the number *n* of cycles leads to lower effective activation energy $U = U_0 - nW$, and so does the level of the energy *W* of a single cycle.

There is an underlying entropy related consideration for the equation (1). From (1) we find:

$$\frac{dP}{dt} = P\exp\left[-\frac{1}{t}\gamma R t \exp\left(-\frac{U_0 - nW}{kT}\right)\right] = -\frac{H(P)}{t} \quad (2)$$

Where

$$H(P) = -P\ln P \quad (3)$$

is the entropy of the distribution (1). The result (2) indicates that this distribution reflects an underlying assumption that the time derivative of the probability of non-failure is proportional to the entropy of this distribution and is inversely proportional to time. The entropy (3) is zero for both the initial moment of time $(t = 0)$, when the probability of non-failure is $P = 1,$ and for an infinitely long time $(t \to \infty),$ when $P = 0.$ This means that this entropy has a maximum in-between. The condition

$$\frac{dH}{dP} = -\ln P_* - 1 = 0 \quad (4)$$

yields:

$$P_* = H(P_*) = \frac{1}{e} = 0.3679 \quad (5)$$

It could be shown that the maximum entropy of the distribution (1) occurs at the moment of time expressed as

$$\tau = \frac{1}{\gamma R}\exp\left(\frac{U_0 - nW}{kT}\right) \quad (6)$$

and this time is assumed to be the mean-time-to-failure (MTTF). Mechanical failure, associated with temperature cycling, takes place when the number of cycles n is

$$n_f = \frac{U_0}{W} \tag{7}$$

When this condition takes place, the thermal energy kT the equation (1) becomes irrelevant, and this equation yields:

$$P_f = \exp\left(-\frac{t_f}{\tau_f}\right) \tag{8}$$

where P_f is the probability of non-failure for the situation when failure occurred, and

$$t_f = \frac{1}{\gamma R_f} \tag{9}$$

is the corresponding lifetime?

Numerical Example

Let, e.g., 20 IC packages have been temperature cycled and the high resistance $R_f = 450\Omega$ considered as an indication of failure, was detected in 15 of them. Then the probability of non-failure is $P_f = 0.25$. If the number of cycles during the FOAT was, say, $n_f = 2000$, and each cycle lasted, say, for 20 min = 1200s, then the time at failure is $t_f = 2000x1200 = 24x10^5 s$ and the formulas (8) and (9) yield:

$$\gamma = \frac{-1n\ P_f}{R_f t_f} = \frac{-1n\ 0.25}{450x24x10^5} = 1.2836x10^{-9}\Omega^{-1}s^{-1},$$

$$\tau_f = \frac{1}{1.2836x10^{-9}\ x450}s = 1731242s = 480.9h = 20.0\ days$$

According to Hall's concept, the energy W of a single cycle should be evaluated by running a specially designed test, in which strain gages should be used. Let, e.g., this energy (the area of the hysteresis loop) was $W = 4.5x10^{-4} eV$ in such tests. Then the stress-free activation energy is $U_0 = n_f W = 2000x4.5x10^{-4} = 0.9eV$. In order to assess the number of cycles to failure in actual operation conditions one could assume that the temperature range in these conditions is, say, half the accelerated test range, and that the area W of the single hysteresis loop is proportional to the temperature range. Then the number of cycles to failure is $n_f = \frac{U_0}{W} = \frac{0.9x2.0}{4.5x10^{-4}} = 4000$. If the duration of one cycle in actual operation conditions is one day, then the time to failure (TTF) is $t_f = 4000\ days = 11.1111\ years$. The probability of non-failure in this case predicted by the formula (8) is $P_f = \exp(-\gamma R_f t_f) = \exp(-1.2836x10^{-9}x450x4000x24x3600) = 2.0126x10^{-87}$ and is next-to-zero indeed.

Conclusion

A predictive model is suggested for the evaluation of the low-cycle-fatigue lifetime of a solder joint interconnection in an avionic IC package subjected to temperature cycling and experiencing low cycle fatigue conditions. Future work should include development of experimental test vehicles for the evaluation of the hysteresis loop for the strain energy for the case of a single temperature cycle, using the today's experimental equipment and techniques; as well as testing for many cycles in order to consider the possible change in the area of the hysteresis loop with time and particularly possible strengthening of the material because of Bauschinger effect.

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