Reliability Tests of Lead Free Solder Joints

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Reliability of RoHS compliant products is investigated in this study. Emphasis is placed on the lead free solder joint reliability. Solder is the electrical and mechanical "glue" of electronics assemblies. Will lead free solders provide the characteristics necessary to allow the world to depend on it in the future? This paper cannot answer this question; however, it will help all participants in the soldering world better understand what needs to be done in order to answer this question and plan for the future.

(I) INTRODUCTION

Since February 13, 2003, RoHS (restriction of the use of certain hazardous substances in electrical and electronic equipment) has been a law in the European Union (EU)[1]. RoHS bans lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr^{6+}), PBBs (polybrominated biphenyls), and PBDEs (polybrominated diphenylethers). The implementation date is July 1, 2006. That means, starting from that date, all EEE (electrical and electronic equipment), except those with exemptions[1, 2, 3], cannot be put on the market of EU if they contain those six banned materials. For the time being, China is considering to have her own RoHS laws.

What is the definition of X-free, e.g., Pb-free? The maximum concentration value (MCV) of those six banned materials permitted in the "homogeneous materials" of an EEE has been published in the EU Official Journal and become a law on August 18, 2005[4]. It stated: "for the purposes of Article 5[1a], a MCV of 0.1% by weight in homogeneous materials for lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) and of 0.01% by weight in homogeneous materials for cadmium shall be tolerated". In plain language, for example, lead free is defined as the content of lead in all the (individual) homogeneous materials of an EEE is less than 0.1wt%.

What is a homogeneous material? It is defined as the material that cannot be disjointed into different materials. For more interpretations of "homogeneous materials[5.]" In this paper, the focus is on Pb (lead) only.

Today, the majority of solder alloy used is the 63wt%Sn37wt%Pb and the melting point is 183°C. Not long ago, there were more than 100 lead free solder alloys, as shown in Table 3[6]. Today, however, the leading lead free solder alloys in the electronics industry are: Sn (3-4) wt%Ag (0.5-0.7) wt%Cu (or simply SAC) and their melting point is around 217°C, which is 34°C higher than that of SnPb solder alloy!

During PCB (printed circuit board) assembly with SAC (instead of SnPb), the components[7,8] and PCBs [9] will be subjected to much higher soldering temperatures and their cost, performance, and reliability are of great concerns[10]. Also, since SAC solder alloys are considerable new to the electronics industry, their solder joint reliability is another great concern[11]. Finally, the energy consumptions with SAC soldering will be increased, e.g., by 18.5% based on a study reported in[12]. Consequently, with SAC, lead free is not good for the electronics industry and the environments.

The reliability of lead free components and the reliability of lead free PCBs are by themselves very important topics. However they will not be discussed herein, where the focus is on the reliability of lead free solder joints.

In the past few years, the most frequently asked questions in lead free products have been:

(1) Are lead free solder joints reliable?
(2) Are lead free solder joints more or less reliable than SnPb solder joints?

It should be pointed out that these are not the correct questions to ask and there are not answers to these questions. In other to ask the right questions and have meaningful discussions, one has to know the REAL definition of reliability and some fundamentals about reliability engineering.

(II) RELIABILITY OF LEAD FREE SOLDER JOINTS

(II-1) Definition of Reliability

Reliability of the solder joint of a particular package in electronics products is defined as the ***probability*** that the solder joint will perform its intended function for a specified period of time, under a given operating condition, without failure [11, 13, 14]. Numerically, reliability is the percent of survivors, i.e., $R(t)=1-F(t)$, where $R(t)$ is the reliability (survival) function, and $F(t)$ is the cumulative distribution function (CDF).

Life distribution is a theoretical population model used to describe the lifetime of a solder joint and is defined as the CDF, i.e., $F(t)$, for the solder joint population. Thus, the one and only way to determine the solder joint reliability is by reliability testing.

(II-2) Objective of Reliability Tests

The objective of reliability tests is to obtain failures (the more the better) and to *best* fit the failure data to (determine the parameters of) the CDF of a chosen probability distribution (e.g., Weibull). The number of items (sample size) to be tested should be such that the final data are statistically significant. The reliability test time is unknown, but usually takes a long time, e.g., a few months.

It should be noted and emphasized that, as soon as the life distribution $F(t)$ of the lead free solder joint of a particular package with certain chip size is estimated by reliability testing, the reliability $R(t)$, failure rate, cumulative failure rate, average failure rate, mean time to failure, etc. of the lead free solder joints are readily determined [11, 13, 14].

Most reliability tests are accelerated tests (with increased intensity of exposure to aggressive environmental conditions, and realistic sample sizes and test times). Thus, acceleration models are needed to transfer the failure probability, reliability function, failure rate, and mean time to failure from a test condition to an operating condition. In establishing the acceleration models of the lead free solder joints, their surrounding materials, (e.g., solder, molding plastic, ceramic, copper, fiber reinforced glass epoxy, and silicon), loadings (e.g., stress, strain, temperature, humidity, current density, and voltage), and failure mechanisms and modes (e.g., overload, fatigue, corrosion, and electromigration) must be considered.

(II-3) Objective of Qualification Tests

Unlike reliability tests, the objective of qualification tests is "PASS" or "NOT PASS" and the test time is well defined ahead of time. As soon as there is a failure before the agreed test time, the test will usually stop and failure analysis is performed to find out why it fails. After all the changes, e.g., re-design, a new qualification test will start again. The sample size of qualification tests is usually less than that of reliability tests.

(II-4) Test Methods

Some common tests for solder joints are:

* Temperature cycling tests (e.g., -25°C to 125°C)
* Power cycling tests (depend on devices)
* Functional cycling tests (depend on devices)
* High/Low temperature storage tests (120°C /-20°C)
* Biased 85/85 tests (e.g., 85°C/85%RH, 1.8V)
* High-voltage extended life tests (e.g., 100°C, 1.8V)
* Pressure cook tests (Autoclave tests) (e.g., 121°C, 2atm)
* Salt atmosphere test (MIL-STD-883D)
* Moisture sensitivity tests (e.g., IPC/JEDEC-020C)
* Shock (Drop) tests (e.g., 1.3 – 1.5mm drops)
* Vibration tests (e.g., random vibration)
* Mechanical bending, shearing, and twisting tests (e.g., IPC/JEDEC-9702)
* Electromigration test [15]
* Others

It should be noted that these test methods can be applied to solder-joint reliability and solder-joint qualification. The key differences between reliability tests and qualification tests are: (1) sample preparation; (2) sample size; (3) test set up; (4) data acquisition system; (5) data extraction method; (6) computer software; (7) test duration; and (8) objective. In this study, only reliability tests will be discussed.

For solder-joint reliability, most of these tests, in general, are very expensive and time consuming. Thus, before and after the reliability testing, design for reliability (DFR) and failure analysis (FA), have been very useful and important tools for solder-joint reliability.

(II-5) Reliability Engineering of Solder joints

Figure 1 shows the concept of reliability engineering of solder joints [11, 13, 14]. It consists of three major tasks, namely, DFR, reliability testing and data analysis, and FA. Usually, the procedure starts with a design of the solder joints with the given IC chip size and package, the solder alloys, and the corresponding PCB, and demonstrates that the design is electrically, thermally, and mechanically sounds. As an example, the DFR activity is often performed with a finite element simulation using the material properties of all the structural elements and the imposed boundary conditions[16-19].

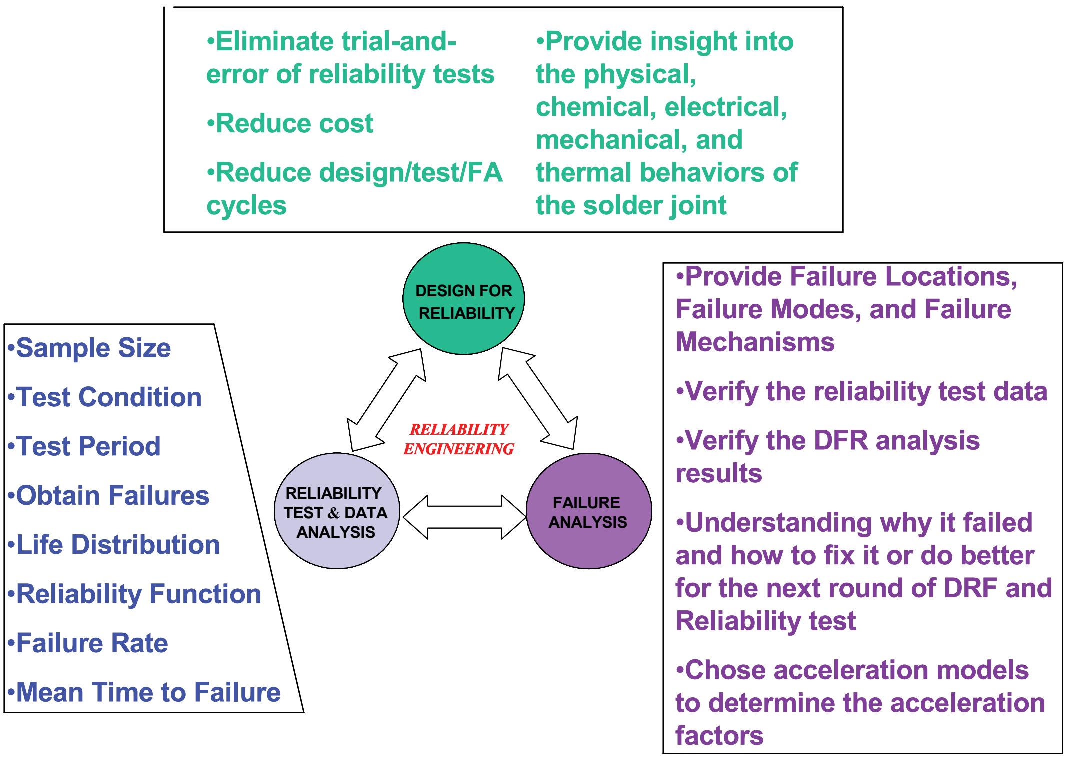


Figure 1 - Reliability Engineering

The next step in the process is for a certain number of samples of the sound or "reliable" design to be built and tested under certain conditions for a certain period of time. The test data are then analyzed and fitted into a life distribution (or reliability) for the solder joints[20];

FA should then be done on the failed samples to understand the reason for their failure[21]. This information is very useful for:

(1) Providing the failure locations, failure modes, and failure mechanisms;
(2) Verifying the reliability test data;
(3) Verifying the DFR simulation results;
(4) Understanding why it failed and how to fix it (or to do better) for;
(5) The next round of DFR and reliability testing; and
(6) Choosing acceleration models to determine the acceleration factors since most of the reliability tests are naturally "accelerated."

Some common methods for solder-joint FA are:

* Visual inspection
* X-ray inspection
* A-, B-, and C-mode scanning acoustic microscope (SAM)
* Dye and pry
* Cross sectioning
* High-power microscope
* Scanning electron microscopy (SEM)
* Focused ion beam (FIB) and SEM
* Energy dispersive x-ray spectrometry (EDX)
* Tomographic acoustic microimaging (TAMI)
* Others

It should be noted and emphasized that the "reliability" obtained from DFR is not the same as the reliability (probability) obtained from reliability tests. For example, the life (number of cycles-to-failure) of the solder joint from reliability tests depends on the percent failed (or survived). Statistically, there are an infinite number of possible lives, e.g., the characteristic life is corresponding to 63.2% failed (or 32.8% survived). On the other hand, the best we can do from DFR is to predict a (one) life of the solder joint for a given boundary condition.

As another example, the failure rate (i.e., the number of solder joints failed in the first year, second year, third year, etc.) can be determined from the reliability test. However, the DFR doesn't even know what 'failure rate' means.

Recently, DFR of lead free solder joints [16-19] is becoming as important as the reliability test; even though it cannot predict the solder-joint reliability, failure rate, mean time to failure, etc. DFR is usually performed by a mathematical modeling based on the material properties of the structure, and laws of engineering and physics in order to:

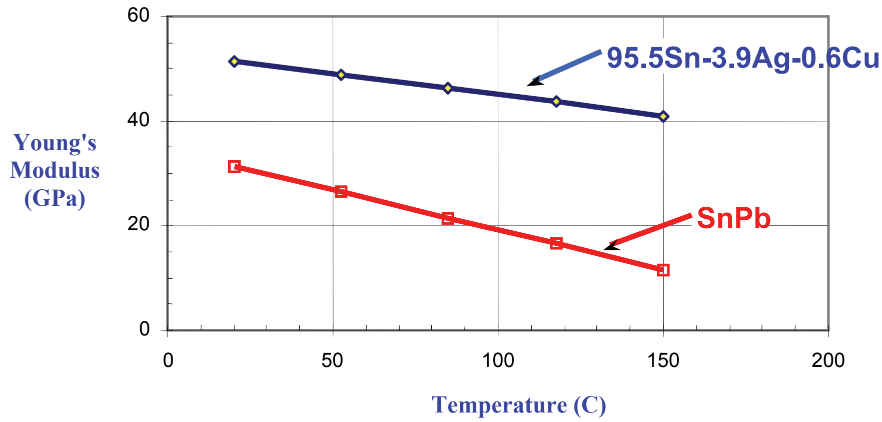
(1) Eliminate trial-and-error of reliability tests;
(2) Reduce cost;
(3) Reduce design/test/FA cycles;
(4) Reduce time-to-market; and
(5) Provide insight into the physical, chemical, electrical, mechanical, and thermal behaviors of the solder joints, e.g., the maximum stress/strain locations – to help test-board designs to capture the most likely (solder joint) failure locations and to help FA to find these failures sites.

(II-6) Material Properties of Solder Alloys

In order to perform DFR and fully understand the engineering physic of solder-joint reliability, the material properties of SAC must be known (through tests) and understood. Some important material properties of solders are[6-11, 16-25]:

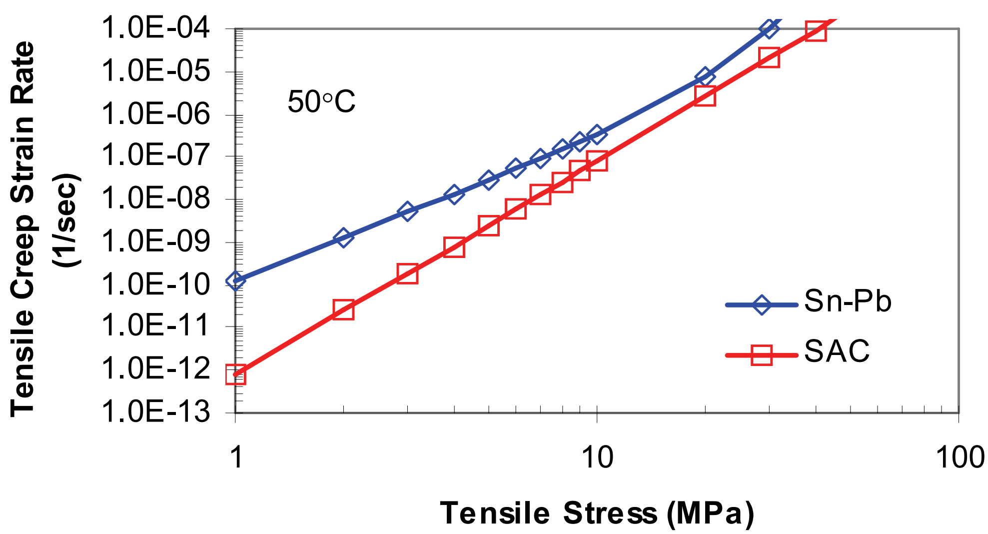
* Phase transition temperatures (solidus, liquidus, plastic, and eutectic)
* Melting point
* Boiling point
* Softening point
* Hardness
* Density
* Dispensability
* Glass transition temperature
* Coefficient of thermal expansion
* Vapor pressure
* Surface tension
* Storage modulus
* Loss modulus
* Viscosity
* Miscibility
* Electrical conductivity
* Thermal conductivity
* Stress-strain curves
* Shear strength
* Tensile strength
* Ultimate strength
* Elongation
* Yield strength
* Young's modulus
* Poisson's ratio
* Creep curves
* Stress relaxation curves
* Creep rates
* Creep rupture
* Fracture toughness
* Viscoelasticity
* Viscoplasticity
* Fatigue strength
* Isothermal fatigue curves
* Fatigue crack-growth curves
* Moisture absorption
* Others

For example, the Young's modulus of the lead free (SAC) and tin-lead (Sn37Pb) solder alloys is shown in Figure 2[23]. It can be seen that the modulus of the lead free solder alloy is larger than that of the Sn37Pb solder alloy. Therefore, for a given structural geometry and boundary condition, one should expect higher stresses in the lead free solder joints when compared to the Sn37Pb eutectic solder joints.



The Young's Modulus of SAC solder is larger than that of SnPb solder. Thus, we should expect higher stresses in the lead free solder joints.

Figure 2 - Young's modulus of lead free and tin-lead solders



For all stresses, the creep rate of SnPb is faster than that of SAC. Thus, larger creep strains in the SnPb solder joints are expected.

Figure 3 Tensile creep strain rate for SnAgCu and Sn37Pb solder alloys at 50°C

For another example, the creep responses of the SAC and Sn37Pb solders at 50°C are presented in Figure 3[24]. It can be seen that the Sn37Pb solder has a creep rate that is greater than that of the SAC. As a result, for a given structural geometry and boundary condition, the Sn37Pb solder joints should have both a faster creep response and higher creep strains.

The cost, performance, quality, and reliability of solder joints will be affected by the above (>35) materials properties of the solder to form the joints. However, it should be re-emphasized that the reliability of solder joints cannot be determined by the material properties of the solder but reliability tests.

(II-7) Quality of Lead free Solder Joints
During lead free process development and manufacturing, the following tests are usually performed:

* Wetting balance test
* Solder spreading test
* Solderability test
* Cleanability test
* Printability test
* Temperature profiling test
* Surface insulation resistance (SIR) test
* Automated optical inspection (AOI) test
* X-ray inspection test
* In-circuit test (ICT)
* Functional test
* Shear test
* Pull test
* Bend tests
* Others!

These tests are very useful for developing the assembly process and for improving the manufacturing yield. Thus, these tests will enhance and ensure the quality of the solder joints. However, these tests cannot determine the solder joint reliability, which has to be obtained by reliability tests.

III. RELIABILITY TEST OF A LEAD FREE PBGA SOLDER JOINTS
Figure 4 shows a very typical Weibull probability plot from the thermal cycling reliability test result of SAC lead free solder joints. In this case, it is for a 256-Pin PBGA (plastic ball grid array) package.

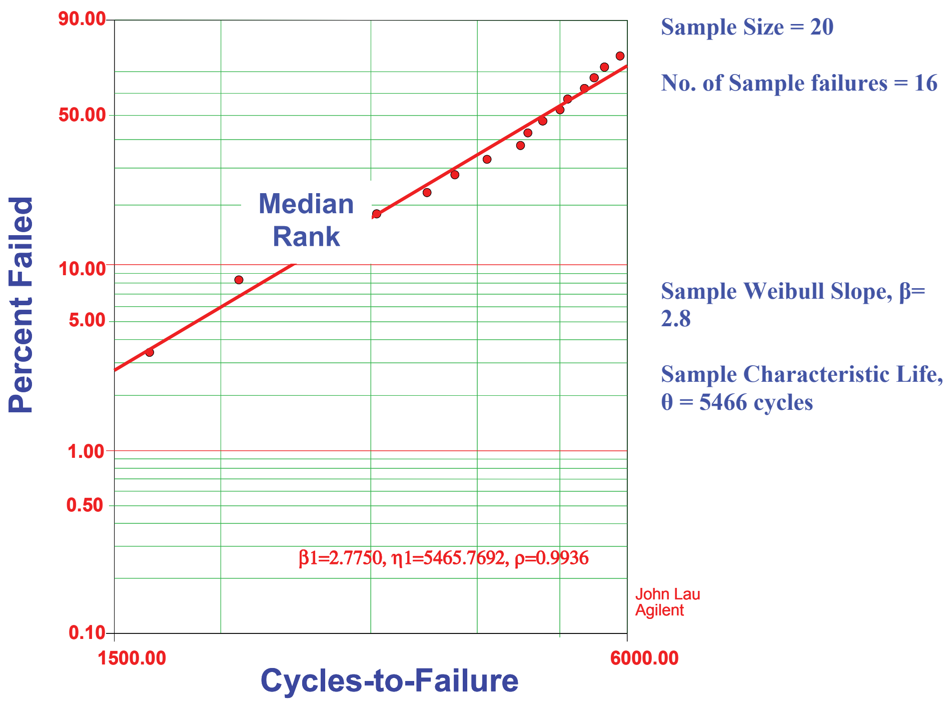


Figure 4 - Thermal cycling test of lead free 256-pin PBGA package on PCB (-25 to 125°C, one cycle per hour)

In order to make Figure 4 meaningful, *all* the following information are necessary [6-11, 16-25]:

* Dummy chip size
* Bismaleimide triazene (BT) substrate material and geometry
* Substrate pad geometry and finish
* Molding compound material and geometry
* Solder ball material, geometry, and pitch
* PCB material and geometry
* PCB pad geometry and finish
* Solder paste alloy, flux, and volume
* Location of voids
* Amount of voids
* Size of voids
* Test board layout (PBGA distribution)
* Daisy chain nets
* Sample size
* Temperature at hot and at cold
* Ramp-up and ramp-down rate
* Dwell-at-hot and dwell-at-cold
* Thermocouple readings (in air) inside the chamber
* Thermocouple readings on PCB
* Thermocouple readings on components
* Thermocouple readings in/near the solder joints
* Data acquisition system
* Data collection method
* Failure criterion and data extraction
* False failures prevention method
* Failure modes
* Number of failures
* Weibull slope error for a given confidence
* True Weibull slope for a given confidence
* True characteristic life for a given confidence
* True mean life for a given confidence
* Others

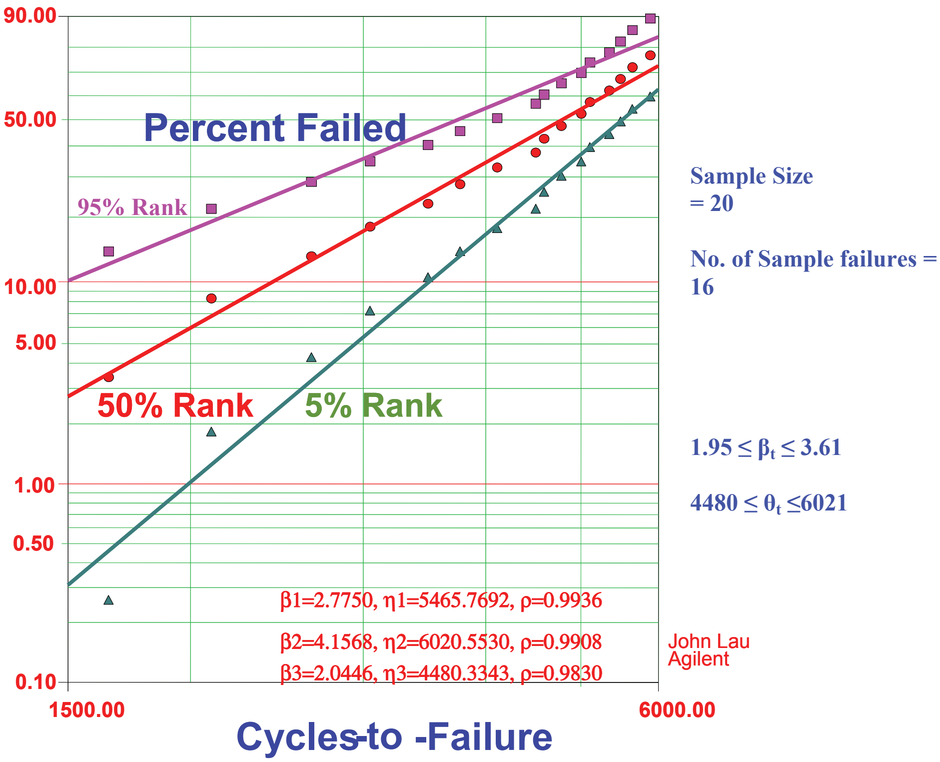


Figure 5 - 256-pin PBGA with 90% confidence (-25 to 125°C, one hour thermal cycle)

From solder joint quality points of view, for example, the last few items are demonstrated in Figure 5. For a given 90% confidence of the 256-Pin PBGA lead free solder joints, i.e., in 90 out of 100 cases, the true characteristic life [11, 13, 14, 20, 25], θ_t, of the 256-Pin PBGA lead free solder joints will happen within the intervals $4{,}480 \le \theta_t \le 6{,}021$ cycles. At the same time, it can be shown that the true mean life (which occurs at 51% failed), μ, of the lead free solder joints, in 90 out of 100 cases (i.e., 90 percent confidence), can be as low as 3,822 cycles and as high as 4,865 cycles, i.e., $3{,}822 \le \mu \le 4865$ cycles. The higher the required confidences the wider the life intervals.

From solder joint uniformity points of view, for example, the true Weibull slope can be estimated from the determination of the Weibull slope error (*E*), which depends on the number of failures (*N*) and the required confidence (*C*) as reported in[11, 13, 14, 20, 25]. For example, in the present case, there are 16 failures ($N = 16$) and the required confidence is 90% ($C = 0.9$), then $E = 30\%$ from Figure 11[25]. Thus, the true Weibull slop, β_t, of the 256-Pin PBGA lead free solder joint can be at least 1.95 but not more than 3.61, i.e., $1.95 \le \beta_t \le 3.61$.

Thus, based on the above requirements and discussions, it can be stated that most published reliability test results are not only meaningless but often misleading. It should be re-emphasized that in order to make the life distribution probability plots such as those in Figures 4 and 5 meaningful, all the (>30) items listed must be clearly stated because they all affect the results.

Now, you have done your reliability tests and data analysis properly and obtained the life distribution, reliability function, failure rate, mean time to failure, etc., so what? How to apply these test results to your products under operating conditions? What are the acceleration factors of lead free solder joints under, for examples, thermal, mechanical, shock & vibration, electromigration, and corrosion conditions? What are the field failure data of lead free solder joints? The industry is still working very hard in these areas.

In many situations, the qualities and uniformities of two products (e.g., two sets of solder joints) are to be compared from the knowledge of the limited test data. One of the difficult tasks in reliability life test is to draw conclusions about a population from a small sample size as shown in the pervious sections. It is even more difficult to compare the populations of two sets of solder joints (e.g., lead free and tin-lead) from the knowledge of their limited test data. If one set of solder joints is found to be superior to another, how ***CONFIDENT*** can it be that the same is true of their populations? (A simple equation reported in[14, 20] can be used to determine this confidence, which is not the same as the required confidence discussed in the pervious sections.)

Now, you have done the reliability tests of lead free and tin-lead solder joints under the same test condition and determined that one is better than the other with very high confidence, so what? How do you know that is also true at operating considerations such as thermal, mechanical, electromigration, corrosion, humidity, current density, shock, and vibration conditions? Again, the industry is still working very hard in these areas!

(IV) SUMMARY AND RECOMMENDATION

The real definition of reliability and some fundamentals of reliability engineering of lead free solder joints have been presented. The key differences between reliability tests and qualify tests have also been discussed. Furthermore, the necessary material properties of lead free solder alloys have been provided. The right questions to ask for lead free solder joints and some useful recommendations are summarized in the following.

(1) What is the ***PROBABILITY*** that the SAC lead free solder joints with certain Ag contents, for certain chip size and components, [e.g., TSOP (thin small outline package), PQFP (plastic quad flat pack), PBGA, CBGA (ceramic ball grid array), CCGA (ceramic column grid array), flip chip, CSP (chip scale package), WLCSP (wafer-level CSP), with various thicknesses and volumes], on certain substrates [e.g., ceramics or organics] or PCBs [with, e.g., OSP (organic solderability preservative), ENIG (electroless Ni immersion Au), ImAg (immersion Ag), ImSn (immersion Sn), or HASL (hot air solder leveling)-SnCu surface finishes and various thicknesses, stiffnesses, decomposition temperatures, glass transition temperatures, coefficients of thermal expansion, etc.], under certain operating conditions [e.g., overload, fatigue, corrosion, electromigration, thermal, mechanical shear, pull, push, bend and twist, humility, voltage, current density, shock and vibration, etc.], for certain periods of time [e.g., 3 years, 5 years, 10 years or 20 years] and will perform certain intended functions without failure?

(2) What are the ***CONFIDENCE LEVELS*** that tin-lead solder joints are more or less reliable than SAC lead free solder joints with certain Ag-content, for certain chip sizes and components, on certain substrates or PCBs, under certain operating conditions, for certain periods of time, and for certain intended functions?

(3) What are the failure mechanisms, failure modes, acceleration models, and acceleration factors of lead free SAC solder joints with certain Ag content, for certain chip sizes and components, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

(4) Are the failure mechanisms, failure modes, acceleration models, and acceleration factors of lead free SAC solder joints with certain Ag content the same as tin-lead solder joints for certain chip sizes and components, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

Due to the immaturity of lead free SAC solder joints; the industry does not have enough data to answer these equations right now. More lead free reliability test data are needed and field failure data must be collected, especially for high-reliability and long life-cycle products. Also, the acceleration factors for lead free solders under temperature, shock, vibration, mechanical shear, pull, twist, and bend, electromigration, corrosion, humidity, current, and voltage conditions are desperately needed. Thus, the reliability of lead free solder joints is currently under scrutiny!

(V) ACKNOWLEDGEMENTS

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