EXPERIMENTAL DATA AND STATISTICAL MODELS FOR OPTIMIZATION OF AGEING MODEL OF LEAD-FREE ELECTRONIC INTERCONNECTION MATERIAL

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Abstract: Modelling and understanding the electrical ageing is a complex phenomenon, in particular for composite material as electrically conductive adhesive consisting of a nonconductive polymer binder and conductive filler particles. This research involves a large amount of parameters related to both operating conditions and material structure, which act together. Accelerated testing used in order to describe the ageing process and to determine the lifetime of these material are difficult to implement with the aim to consume rapidly lifetime without inducing incorrect failure mechanisms. Further difficulties are the implementation of the right chemico-physical ageing model for lifetime prediction under accelerated testing and new statistical approach for reliability data analysis and treatment.

Keywords: Accelerated life testing, ageing, electrically conductive adhesive, experimental design, lifetime data.

1. INTRODUCTION

With the introduction of new material in electronic devices, it is necessary to guarantee its high reliability overall in application such as military, aerospace, telecommunication, medical implants, and so on. In particular, the assessment of the reliability of new material is a non-trivial challenge [1], because of the new material structures and the absence of field data [2].

Material as Electrically Conductive Adhesive (ECA), that can be used in electronic devices as electrically conductive and packaging materials, would have a great future in electronics, in particular, in implantable and in printing medical devices or in optics on fiber, LED and LCD if it will be also characterized by high reliability. In fact, unexpected failure of these material results in safety risks, damage and consequential costs.

In order to estimate the expected lifetime of material/component/device is to put them in the real operating environment and monitor them when they would die. Being this method not workable because it would cost too many time before the products can be sold, the accelerated life test is proposed to solve this issue. The main goal of lifetime studies is to establish a relationship for the aging process and the stresses causing it, suggest mathematical models, and to verify them. All this is done through an accelerated process, and the results applied to normal operating conditions. Therefore, being able to predict end of life with certain degree of accuracy in a short time span by accelerating the aging process is very useful to design engineers. There are several ways to accelerate the aging process. The most popular are experiments performed at environmental, mechanical and electrical stresses much higher than normal operating conditions. And the method of stress application (constant or time varying) is fundamental in the life model implementation.

Considering that the first application of this material is the soldering in electronic devices, it is necessary to ensure extremely resistant joints, able to sustain the unavoidable electrical, mechanics and environmental stresses that take place during the operating life. Specimens with material were realized for this purpose. Several accelerated models were proposed in literature to obtain lifetime data, considering thermal fatigue, vibration, electrical solicitation or their interaction, for soldering material alloy [3-5], instead there is a lack of studies on new ECA accelerated life model and the relative experimental data analysis [6].

The samples are generally aged for several designated time spans and examined for physical and chemical changes; the scatter in the experimental data from any lifetime test advocates the application of statistical methods which are briefly described in the section below. Statistics is frequently used to predict life expectancy. To properly evaluate the data, certain steps are required: Weibull probability distribution and recent contributes are evaluated in order to consider the specific features of lifetime experimental data and modeling [7]. In particular, the structure of the experimental data relating to the statistical modeling approach implies the consideration of random effects and Bayesian methods [8].

2. QUANTITATIVE ACCELERATED LIFE TESTING

A variety of methods that serve different purposes have been termed "accelerated life testing". As we use the term in

this reference, accelerated life testing (ALT) involves acceleration of failures with the single purpose of quantification of the life characteristics of the product at normal use conditions.

More specifically, accelerated life testing can be divided into two areas: qualitative accelerated testing and quantitative accelerated life testing. In qualitative accelerated testing, the engineer is mostly interested in identifying failures and failure modes without attempting to make any predictions as to the product life under normal use conditions. In quantitative accelerated life testing, the engineer is interested in predicting the life of the product (or, more specifically, life characteristics such as Mean Time to Failure) at normal use conditions, from data obtained in an accelerated life test.

Quantitative accelerated life testing consists of tests designed to quantify the life characteristics of the product, component or system under normal use conditions and thereby provide reliability information. Reliability information can include the determination of the probability of failure of the product under use conditions, mean life under use conditions and projected returns and warranty costs. It can also be used to assist in the performance of risk assessments, design comparisons, etc.

Quantitative accelerated life testing can take the form of usage rate acceleration or overstress acceleration. A simply way to accelerate the life of many products is to run the product more at a higher usage rate. Overstress acceleration, instead, consists of running a product higher than normal levels of some accelerating external stress (es) to shorten product life or to degrade product performance faster. Typical accelerating stresses are temperature, voltage, mechanical load, thermal cycling, humidity or vibration. Overstress testing is the most common form of accelerated testing.

In order to plan and implement quantitative accelerated life testing could be useful follow the flow chart showed in Fig. 1, in which the identified steps are the following:

1. Choice of failure mechanism to be analyzed
2. Identification of the stress that activates failure mechanisms and its application mode
3. Selection of a Life Distribution
4. Selection of a Life-Stress Relationship/Model
5. DoE Planning and Implementation – Statistical Model Definition
6. Test Planning and Implementation
7. Data Analysis and Parameters Estimation
8. Predicted Values of Reliability Information (in operative conditions).

3. ELECTRICALLY CONDUCTIVE ADHESIVE

Electrically Conductive Adhesive (ECA) is a material consisting of epoxy resin filled with metal particles. All electrically conductive adhesives have two common qualities: they provide a chemical bond between two surfaces and they conduct electricity.

In particular we focused on an isotropic material which is conductive in all directions (ICA). Isotropic conductive materials conduct electricity in all directions equally, and can be used to replace solder on thermally sensitive components. Isotropic materials can be used on devices that require a ground path. Electrically conductive isotropic adhesives can be used as an electrical interconnect on non-solderable substrates such as ceramic or plastics, or to replace solder on thermally sensitive components that cannot withstand > 200°C solder processing temperatures [9–11].

The most popular filler material for highly conductive adhesives is silver due to its moderate cost and superior conductivity. Silver Isotropically Conductive Adhesives (Ag-ICA), constituted by epoxy resin that is not conductive, becomes conductive when metallic particles such as silver are added, thus creating continuous bridges that guide the current inside the material. Isotropic silver-filled epoxies can be worked at heat or room temperature curing, and can be found in single or two component formulations. Since electrically conductive epoxies require temperatures of only 150°C or less to cure, isotropic epoxies are an ideal alternative to solder on thermally sensitive parts.

In this case-study, a one-component adhesive, Heraeus, and a two-component adhesive, Epotek, were examined and compared. They are characterized by different distribution, shape, size uniformity and quantity of metal particles drowned in the epoxy resin. Heraeus PC3000 has viscosity value equal to $15 \div 25$ Pa*s (at 50 s-1, 23 °C) and Epotek H20E has $2.2 \div 3.2$ Pa*s (at 100 rpm, 23 °C) as viscosity value.

In order to study the reliability performance of these materials, specimens were implemented according to a specific geometry and a proper procedure as shown in [12].

The parameter chosen to monitor the degradation of the materials is the electrical resistance.

4. EXPERIMENTAL DATA AND STATISTICAL MODELS

In this paper, statistical methods are carried out in order to study product lifetime and, in particular, ECA lifetime. More precisely, the first step of the analysis should consider the planning of trials by evaluating the specific features and characteristics of the involved ECAs and, in addition, the environmental and noises factors which can be included in lifetime experiments to stress the ECAs performances. Secondly, specific statistical models for reliability data analysis are applied.

4.1 PLANNING OF THE EXPERIMENTAL DESIGN

The design of experiment is a wide and fundamental methodology of the statistics theory; at the beginning, the classical experimental design was mainly directed to study specific problems sourcing in agriculture; therefore, some basic and classical definitions, like the definition of blocks and sub-experimental factors or Latin-square designs, were related to this specific kind of applications [14]. Nevertheless, since 1950s, many theoretical developments have been formulated in order to extend the basic and

simple classical designs and linear modeling; furthermore, these new theoretical issues have been differently developed by considering the specific fields of application. Optimal design criteria and Response Surface Methodology (RSM) date back to this period.

A great impulse to the evolution of experiments theory was further originated by the technological field and the concept of quality improvement. The study of quality products or processes involving the design of experiments dated back since 1940s and the definition of the fractional factorial design together with RSM has been largely developed especially in 1980s and 1990s; the robust design approach through RSM [15, 16] or Generalized Linear Models (GLMs) [17-19] gave a notably boost to the use and application of design of experiments in new fields.

In this context and more recently, reliability statistical analysis has requested a systematic collection of data which has been naturally lead to the use of the experimental design theory [20]. Undoubtedly, reliability analysis is a great challenge for experiments relating to specific issues, such as the structure of data and the corresponding non-linear statistical models (Section 4.2).

In our case study, the planning of the experimental design has been built starting from the experimental design planned for the ECA's optimization process [12]. Furthermore, we may ideally divide the experimental programming in two steps: i) the first step relates to the planning and optimization in order to set an optimal solution for ECA's following the robust design concepts; ii) the second step uses the experimental trials carried out at the first step.

By considering this second step, each ECA is separately planned through the 18 runs of the first step; each run is stressed by Thermal Cycling Test (TCT). We decided to plan Thermal Cycling Test in order to induce crack or resistivity variation in specimens and then to implement ECA thermal cycling solder joint reliability. This experimental approach will be used to study the effects of maximum temperature, ramp rates, dwell times, that are temperature profile (trapeze-like cycle) on ECA solder joint life. A detailed study of maximum temperature, dwell time and ramp rate effects will carried out and we hypothesize that the study of the possible effects will show how accelerated thermal cycling profiles can be optimized to improve test efficiency. ECA life could vary with the selected factors because damage in the ramp is affected by strain rate, temperatures and times within ramp. Furthermore, damage in dwell is affected by preceding strain rate, temperature and time within dwell.

In this work, the sensitivity to maximum temperature and temperature range will be studied. This experimental study evaluates the maximum temperature and, consequently, the temperature range vary. Note that the considered temperature range could vary from 100 °C to 150°C. Intuitively, we expect that cycles to failure progressively decreases with the increase in temperature range, consequently with the achievement of maximum temperature. We decided to fix at 25°C the minimum temperature profile, that will be the reference temperature at

which the electrical performance of the tested material will be measured.

The ramp rate is characterized by a nominal value of 1°C/min. The studied ramp rates reach as maximum value 5°C/min. Higher ramp rates are not considered as they may lead to interaction from mechanisms other than those considered in this paper. This study is of particular interest since no definitive experimental results are available in the literature on the effect of thermal ramp rate on cycles to failure.

The dwell time for the nominal value is 10 minutes. The other investigated dwell time values achieve the maximum value to 30 min, considering that the increasing dwell time at high temperature decreases the life, but with decreasing sensitivity when dwell time increases [21].

We expect that life will have dependence from the selected factors, it will suggest sensitivity to different material properties in ramp and dwell. In fact, we suppose that there will be dependencies and potential interactions to address through the implemented statistical methods.

The choice of level factors allows us to increase the stress severity in order to induce acceleration in material degradation. After the implementation of the reliability study, it will be important to extrapolate the acceleration factor (AF) and its sensitivity to the other factors and corresponding levels. After the Accelerated TCT, it will be interesting to evaluate the coefficient of thermal expansion on the tested ECAs in order to understand the predicted use of these new lead-free materials in electronic devices.

It must be noted that the response variable is the electrical resistance in both experimental steps, however, in the second experimental step we have multiple electrical resistance response variables, each collected at a specific value of thermal cycle t (t=1,…T). Thus, Y_{it} is the electrical response variable related to the i-th trial collected at cycle t.

We suppose that these T response variables will be strongly correlated and, obviously, we do not know a-priori the amount of failures at cycle t.

Two relevant issues should be evaluated during the experimental planning and subsequent analysis:
1) for each specimen, a random allocation is performed between the two experimental steps; thus, a random effect will be evaluated in the statistical model;
2) at least two specimens are considered for each trial of the new second experimental design.

Therefore, the final experimental design for the second step is a complete factorial design with three factors at two levels and two center point replications. Through this experimental design it is possible to estimate the three first order interactions, even though only two specimens are analysed for each new trial.

4.2 THE STATISTICAL MODEL

In this regard, specific statistical models should be applied in order to consider the aforementioned situation and, eventually, non-linear effects. Particularly, in the recent literature, extensions to previous statistical reliability models are introduced to treat experiments not coming from CRD

[8] together with non-fixed effects [7]. Thus, Weibull non-linear mixed models can be applied to evaluate blocks and random effects.

The two-parameter Weibull distribution has the following Probability Distribution Function (PDF) for N statistical units (i=1,..N):

$$f(t_i) = \frac{\beta}{\eta}(\frac{t_i}{\eta})^{\beta-1} e^{\frac{t_i^\beta}{\eta}} \qquad (1)$$

Where β>0 and η>0 are the shape and the scale parameters, respectively.

And the corresponding likelihood function is:

$$l(\beta, \eta) = \prod_i f(t_i) \qquad (2)$$

It must be noted that this expressions are related to a life test data for a CRD according to [13].

Furthermore, when considering the Weibull distribution, formula (1), and reliability statistical data, a further issue should be taken into account.

In fact, in this case, the specific structure of data is strictly tied to the estimation of the corresponding statistical model: often, experimental units do not have the same failure time. Thus, censored data are generated and specific type of censoring may be defined. For example, two common types of right censored data are Type I and Type II, related to time censored and failure censored, respectively. When considering these two types of censored data, the likelihood becomes:

$$l(\beta, \eta) = C \prod_i [f(t_i)]^{\delta_i} [1 - F(t_i)]^{1-\delta_i} \qquad (3)$$

where δ_i is a dummy variable specified for each statistical unit and it is equal to zero if the unit is right censored and equal to one if observed; $F(t_i)$ is the cumulative distribution function, while C is a constant which varies according to the kind of censoring.

5. CONCLUSION

This paper reported on work in progress on an ECA solder joint life prediction model and ECA acceleration factors, by means of the implementation of accelerated thermal cycling tests planned through a proper DOE.

In its present condition, the model applies only to leadless electric conductive adhesive, an extended version could include also the effect of local CTE mismatches, an important factor for attachment reliability of leaded packages. The present model was used to better understand the response of SAC solder material under thermal cycling conditions. The statistical model, which has also been validated for maximum temperature, dwell time and thermal rate effects, can be used to optimize accelerated test conditions. This experimental study, from the point of view of test engineers, brings to the optimization of maximum temperature, ramp rate and dwell times for best test-time compression. In industrial world solder interconnects or electronic packages are typically tested under accelerated laboratory conditions, so the test time compression is important also from an economic point of view. The most significant contribution of this study is that a rigorous statistic approach to the implementation of SAC reliability model is now available, to predict cyclic durability based on test data.

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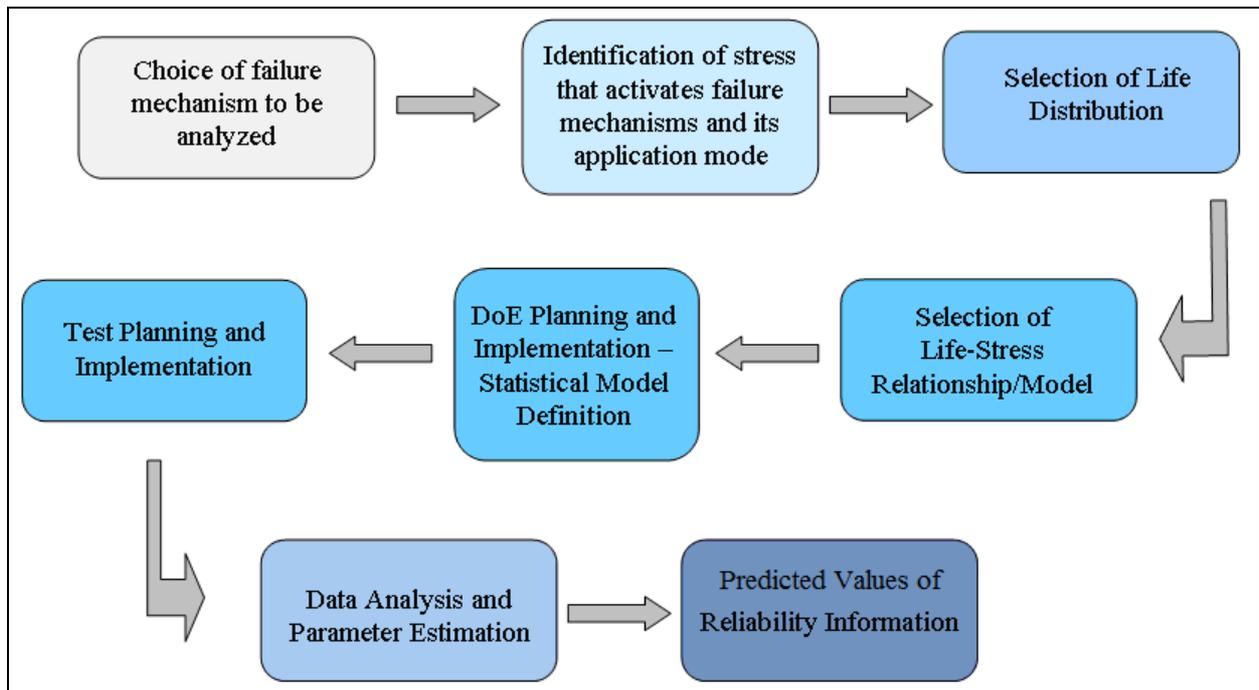
Figure 1: ALT flow chart