

# Analysis of Pb-free BGA Solder Joint Reliability Data

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## Abstract

As the electronic industry has been focusing on eliminating lead (Pb) from the product manufacturing processes to meet the EU RoHS Directive, numerous studies on lead-free interconnect reliability have been published and more will be available to the public in the near future. The purposes of this study are to perform such an analysis on current available Pb-Free package reliability data to first sort out the most significant attributes and the critical areas so that more attention can be paid on them in the future; and second establish a stochastic model that can be used to predict solder joint life when a quick reliability evaluation is needed but the test results is not readily available. Based on more than 200 test data points from publications and internal qualification tests that cover a wide range of package types (FCBGA, PBGA, TBGA, etc), most commonly used lead-free solder compositions (SnAgCu, SnAg, etc), and most industry standard accelerated test conditions, this analysis helps us to better understand how Pb-free solder joint behavior under different test conditions.

Key words: Pb-free, solder joint, reliability, stochastic, data analysis

## Introduction

The microelectronic industry has been putting efforts to remove or eliminate lead (Pb) from the products and related manufacturing processes in order to meet the EU RoHS Directive. Numerous studies on lead-free interconnect reliability have been published [1-24] and more shall be available in the near future. It is critical to look at those valuable data in a whole so that some general trends or characteristics could be explored to help us better understand how Pb-free solder joints behavior under various conditions. The majority of reliability data analyzed in this paper were from references [1-24] that covered a wide range of package types, solder compositions, and accelerated thermal cycling (ATC) conditions, therefore should be a good representative of current status of Pb-free package reliability. With help of a statistical analysis software, such as JMP [26], the authors have demonstrated [27] that excellent stochastic models could be generated for organic packages (packages with laminate, build-up, or tape substrate), ceramic packages (packages with Alumina substrate, high CTE ceramic substrate, or wafer level CSP), and leadless packages (QFN and LCCC). Since the organic packages comprise of most of the Pb-free BGA packages commonly used today, further analysis is presented in this paper to have a through investigation on the relationship between Pb-free joint of organic packages and key attributes.

## Overview of Pb-free solder joint reliability data analysis

The key for a successful data analysis is to sort out the major parameters that have significant contributions to the results. Solder joint itself is a complex material system which usually used as interconnects between components and print circuit boards (PCB). Therefore solder joint reliability is a function of numerous factors such as packaging material, package structural construction, assembly process, and test conditions etc. For convenience, those parameters can be categorized into component related, PCB related, assembly related, and accelerated thermal cycling (ATC) related as follows:

- Component
  1. package type (FCBGA, PBGA, etc)
  2. package size
  3. die size
  4. die thickness
  5. die/package area ratio
  6. I/O count
  7. substrate thickness
  8. substrate layer count
  9. ball pitch
  10. substrate pad type (solder mask defined (SMD) or non-solder mask defined (NSMD))

11. substrate pad size
12. substrate pad finish
13. BGA ball diameter
14. BGA ball metallurgic composition
- PCB
  1. PCB thickness
  2. PCB material
  3. PCB pad type
  4. PCB pad size
- Assembly
  1. assembly configuration (single-sided or clam-shell)
  2. solder paste composition
  3. flux type
  4. stencil aperture
  5. stencil thickness
  6. reflow peak temperature
  7. reflow time above liquidus (TAL)
  8. post assembly standoff
- ATC
  1. cycling peak temperature, Tmax
  2. cycling temperature range, dT
  3. hot dwell time
  4. cold dwell time
  5. ramp rate
4. Package pad type: solder mask defined (SMD), or non-solder mask defined (NSMD)
5. Package pad size, mm: 0.25 – 0.65
6. Package ball diameter, mm: 0.3-0.76
7. Package size, mm: 8 - 50
8. Die size, mm: 4 - 20
9. Die thickness, mm: 0.175 – 0.725
10. Die/Package area ratio: 5% - 77%
11. PCB thickness, mm: 0.8-3.3
12. SMT configuration: single-sided, or double-sided (clam-shelled)
13. Solder paste composition: no paste, SAC105, SAC305, SAC387, SAC395, or SAC396
14. ATC peak temperature Tmax, Celsius: 75 - 125
15. ATC temperature range, dT, Celsius: 50 - 165
16. ATC hot dwell time, min: 5 - 60
17. ATC cold dwell time, min: 3 - 15
18. ATC ramp rate, C/min: 7.5 - 15

Some of the above parameters are readily available from qualification reports or package detail description, some would be available only after performing failure analysis (FA), therefore it is critical to keep record and document all information related to the qualification test vehicles.

### Key attributes of Pb-free organic packages

The solder joint life of organic packages is governed by more factors than ceramic or leadless ones due to the complex stress state on their solder joints. Listed below are the attributes and their ranges used in model fitting of this study. Since some of the joint metallurgical compositions in this study have little test results, the data has been regrouped by the Ag weight content of solder alloy. To simplify the analysis, the ATC ramp rate, Celsius/minute, has been used instead of the ramping time. For Pb-free organic packages, these attributes are commonly available in the qualification test reports or publications [1-25]:

1. BGA solder composition: low Ag content ( $\leq 2\%$ ), mid Ag content ( $> 2\%$  but  $< 3\%$ ), or high Ag content ( $\geq 3\%$ )
2. Substrate thickness, mm: 0.12 - 1.18
3. BGA ball pitch, mm: 0.4 - 1.27

The model that consists of these 18 attributes as the 1<sup>st</sup> order terms accounts for 87% of the Pb-free solder joint life change. The model fitting is shown in Figure 1. To achieve better fitting, one could add more factors if information available or consider the coupling effects of the existing factors to include 2<sup>nd</sup> or higher order terms in the model. The drawback of higher order fitting is that the sensitivity analysis is not feasible anymore as the higher order terms may not have physical meanings [27].

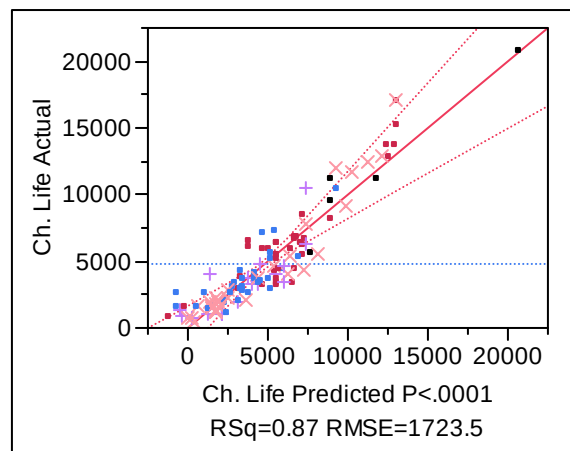


Figure 1. 1<sup>st</sup> order fit with common factors

### Sensitivity analysis of the attributes

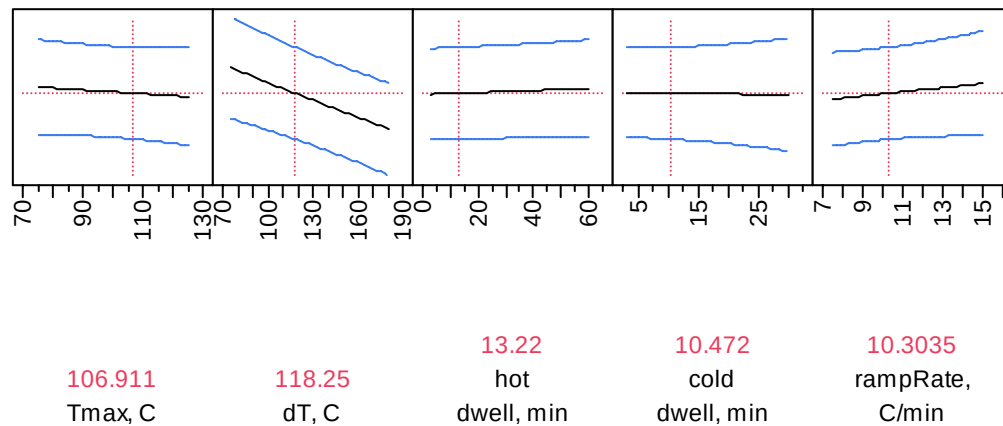
The first order fit model can be used to study the how sensitive the solder joint life to the change of a

particular attribute, which provide us a convenient way to understand how solder joint behaves when one or a couple of attributes change in certain way.

#### ATC related attributes

Figure 2 shows the dependencies of Pb-free solder joint life to ATC conditions. For the data analyzed,

the solder joint life of Pb-free organic packages showed higher sensitivity to the ATC temperature range  $dT$  but not so much to the ATC peak temperature  $T_{max}$  or the dwell time (both hot and cold), indicating that increase the dwell may not be an efficient way for accelerating the damage.

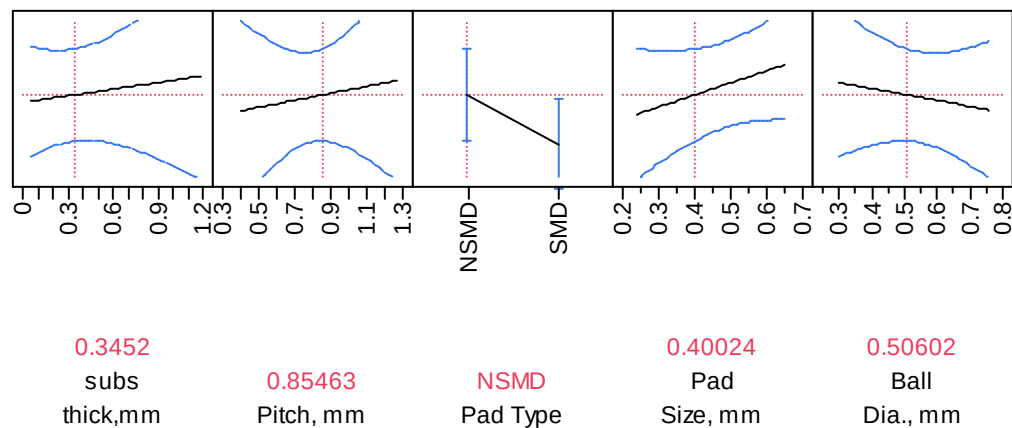


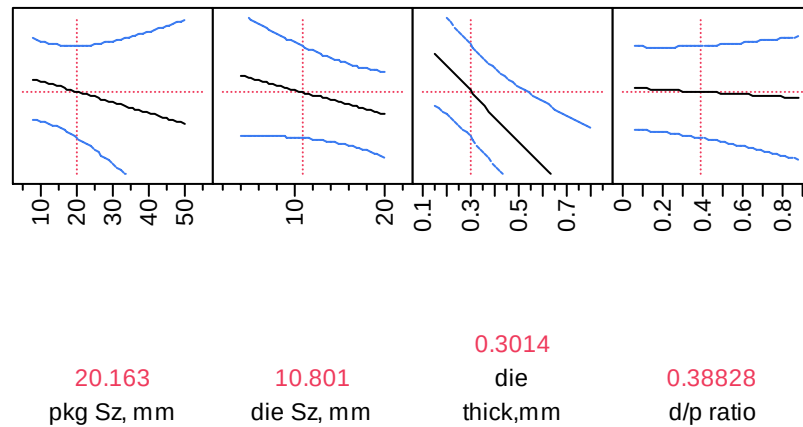
**Figure 2. Impact of ATC conditions**

#### Component related attributes

The impact of component related attributes is shown in Figure 3. Not much to one's surprise, the solder joint life benefit from thicker substrate, larger ball pitch, and large pad size. NSMD packages does perform better than SMD ones. On the other hand, package body size, die size, and particularly the die thickness significantly lower the solder joint life as one would expect. The model also showed that

attaching larger diameter BGA balls actually has detrimental effect on solder joint life, since the actual standoff of these packages were not available further analysis would be needed to solve the puzzle. Ideally the model should include some assembly related parameters such as the actual paste volume to reveal the dependencies of joint life to parameters like BAG ball diameter.



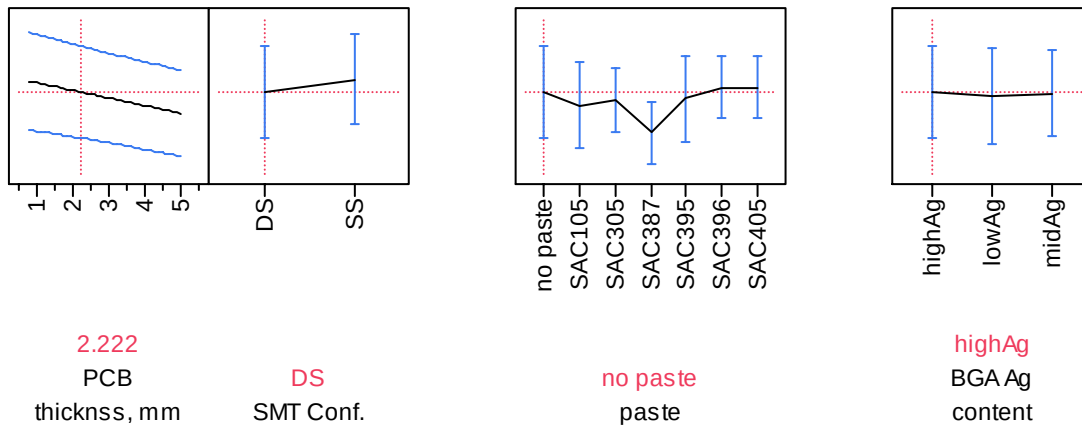


**Figure 3. Impact of component related factors**

#### Other attributes

Figure 4 shows the sensitivity trend of other attributes in the model. As expected, the joint life is lower for packages assembled onto a thicker PCB or in double-sided configuration. The data showed no big difference between all Pb-free SAC alloy joints. Similarly the model showed weak dependencies

between joint life and the paste compositions. It seems that higher Ag content paste improves though insignificantly solder joint life except SAC387 which is the worst among all. Due to the information availability of assembly related parameters, it is difficult to differentiate the lumped effect to the parameters included in the model.

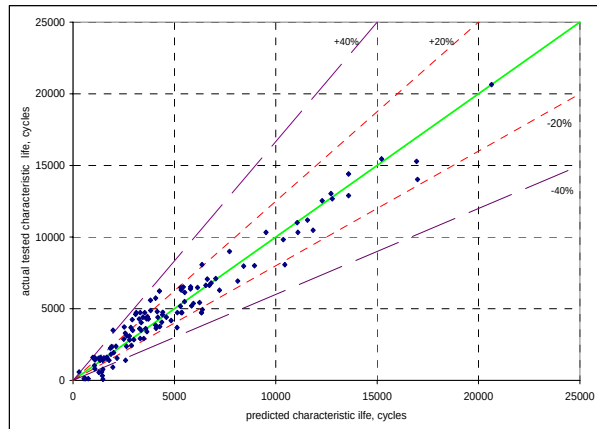


**Figure 4. Impact of other factors**

#### The stochastic prediction model

In order to achieve better fitting results, a stochastic model has been generated using stepwise fit to include the significant square and cross-product terms. For the analyzed data, 95% of the solder joint life change is predictable by the outcome stochastic model. The comparison between the actual test

results and model prediction is showed in Figure 5. All model predictions are within 40% of relative error range compared to the actual tested life. The stochastic model, in polynomial style, is convenient to use and could be easily exported out from JMP.



**Figure 5. comparison between actual test results and the model predictions**

### Conclusions

A methodology to perform reliability data analysis and build simple but accurate stochastic prediction model for Pb-Free packages has been demonstrated. The model, driven by the test data, can be used to study the sensitivity of the key parameters that affect Pb-free solder joint reliability. The data analysis would help us to gain insight and better understandings of the Pb-free solder joint behavior under different conditions. Compared to the current available Pb-free solder joint reliability data, most of the model predictions are within 40% relative error range. This simple model is very useful for risk assessment in product development while the qualification testing is yet to be finished. The model could also be used in planning the qualification testing.

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