Effects of Dwell Time and Ramp Rate on Lead-Free Solder Joints in FCBGA Packages

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Abstract

Many studies on eutectic solder [1,2,3] have shown that the dwell time beyond certain limit has a minimal effect on the MTTF. Additional dwell time will not produce additional damage beyond a limit or boundary. However, our experiments consistently showed that the fatigue life of the lead-free solder balls decreases significantly when the dwell time increases from 15 minutes, to 30 minutes and until 90 minutes. Further failure analysis confirms that the failure mode and failure location is same when dwell time changes. The longer dwell time is, the more accumulated creep damage is. The results imply that it takes long time to entirely achieve the relaxation for the lead-frees solder material. In addition, results also showed that the lead-free solder joint during thermal shock fails faster than thermal cycling. The faster ramp rate does impose more damage on solder joint than a slow ramp rate. It is concluded that the ramp time and dwell time have conflicting effects on solder joint reliability. Finite element analysis is conducted to have a fundamental understanding of the effects of ramp rate and dwell time on lead-free alloys. A remarkable agreement on the correlation between the finite element analysis and experimental results was achieved. The numerical results revealed the failure mechanism of solder joint associated with the ramp rate and dwell time. Thermal shock has a much faster ramp rate, thus imposing much more damage to the solder joints than thermal cycling. In that sense, the fatigue life decreased when the frequency increased. However, a longer dwell time causes more creep in the solder joint, thereby lowering the fatigue life significantly. This means that fatigue life decreases when frequency decreases. It can be concluded that frequency as a single parameter for a reliability model doesn't account for the conflicting effects of ramp rate and dwell time. The finite element results also show that the majority of damage occurs during the ramp period. The dwell time at high temperature is predicted to have a negligible contribution to the total inelastic strain energy density

Introduction

Lead-free solder is fast becoming a reality in electronic manufacturing due to marketing and legislative pressures. The industry has decisively concluded that various versions of SnAgCu solder alloy offer the best alternative to the eutectic Sn/Pb solder currently in use. With the current trend of cheaper, faster, and better electronic equipment, it has become increasingly important to evaluate the package and system performance very early in the design cycle using simulation tools. However, complex nonlinear acceleration behavior of SnAgCu solder alloy has presented special challenges in relating the stress conditions to use conditions.

The accumulated per-cycle total inelastic strain energy density (ΔW), creep strain energy density (ΔW_{creep}), inelastic strain ($\Delta\varepsilon$), or creep strain ($\Delta\varepsilon_{creep}$) have long been recognized as parameters to replace the temperature range ΔT in Coffin-Mansion-based equations [e.g. 4-11]. ΔW (or $\Delta\varepsilon$), the permanent per-cycle damage in the material, not only reflects the effect of temperature change ΔT , but also the effects of package geometry (e.g. solder joint layout, die-size, etc.), material properties, and loading conditions (e.g. dwell time and ramp rate). However, the interpretations of ΔW-based Coffin-Manson equations can be different. Most of the ΔW based Coffin-Manson equations use the characteristic life related to ΔW directly, in which the characteristic life is derived from electrical failures during temperature-cycling stress tests [e.g, 4, 6]. Darveaux [5, 10] proposed an alternative approach, in which ΔW is related to both crack initiation and crack propagation. Therefore, the number of cycles to failure can be defined as the number of cycles to full crack propagation.

A temperature cycling profile is characterized by the temperature extremes, ramp rates and dwell times. Therefore an understanding of the relative effects of ramp rate versus dwell time on the deformation kinetics and damage mechanisms of solder joints connecting packages and PC board during thermal cycling is essential. Many studies have investigated the impact of cycling frequency, and concluded that the fatigue life has an inverse power law relationship with the frequency, such as the well-known Norris Landzberg equation [12]

$$AF = (\Delta T_{use}/\Delta T_{test})^{-n}(f_{use}/f_{test})^{m} \quad (1)$$

where ΔT_{use} and ΔT_{test} are temperature ranges at use condition and test condition, respectively. f_{use} and f_{test} are frequencies at use condition and test condition respectively. However, the above equation doesn't account for the conflicting effects of ramp rate and dwell time.

In order to have a fundamental understanding of the effects of ramp rate and dwell time on lead-free alloys, finite element analysis is performed in this paper. The numerical results revealed the failure mechanism of solder joint associated with the ramp rate and dwell time. Thermal shock has a much faster ramp rate, thus imposing much more damage to the solder joints than thermal cycling. In that sense, the fatigue life decreased when the frequency increased. However, a longer dwell time causes more creep in the solder joint, thereby lowering the fatigue life significantly. This means that fatigue life decreases when frequency decreases. An extensive design of experiment (DOE) has been conducted to understand the effects of dwell time, maximum temperature, and ramp rate for FCBGA package with

SnAgCu solder alloy to validate the finite element modeling results.

Analysis Approach

The Anand model in commercial software ANSYS has been used here to characterize the rate-dependent creep behavior of solder alloys at varying temperatures. In Anand model, the flow equation is,

$$d^{p} = A e^{-\frac{Q}{R\theta}} \left[\sinh\left(\xi \frac{\sigma}{s} \right) \right]^{1/m} \tag{2}$$

and the evolution equations are

$$\dot{s} = \left\{ h_0 (|B|)^{a} \operatorname{sgn}(B) \right\} d^{p}$$

$$B = 1 - \frac{s}{s^{*}}$$

$$s^{*} = \hat{s} \left[\frac{d^{p}}{A} e^{\frac{Q}{R\theta}} \right]^{n} \tag{3}$$

where d^p is the effective inelastic deformation rate, σ is the effective Cauchy stress, s is the deformation resistance, s* is the saturation value of deformation resistance, ś is the time derivative of deformation resistance, and θ is the absolute temperature. Viscoplasticity is defined here by unifying plasticity and creep. There is no explicit term in Anand model to account for rate-independent plasticity.

Darveaux [5,10] gave the nine material constants in equations (2)-(3) for eutectic solder alloys. This has led the Anand model very popular in solder joint reliability modeling. For SnAg alloys, there are several versions of material constants published in literature such as [e.g. 13, 14 and 15]. This paper uses the material constants given by Wang etc [13]. Table 1 [13] lists the Anand's model constants for different solder alloys including SnAg.

Table 1 Material parameters of viscoplastic Anand model for solders

Material Parameters	Solders			
	60Sn40Pb	62Sn36Pb2Ag	96.5Sn3.5Ag	97.5Pb2.5Sn
A (s^{-1})	1.49(10^7)	2.30(10^7)	2.23(10^4)	3.25(10^{12})
Q/R (°K)	10830	11262	8900	15583
ξ	11	11	6	7
m	0.303	0.303	0.182	0.143
$\hat{s}$ (MPa)	80.42	80.79	73.81	72.73
n	0.0231	0.0212	0.018	0.00437
h_0 (MPa)	2640.75	4121.31	3321.15	1787.02
a	1.34	1.38	1.82	3.73
s_0 (MPa)	56.33	42.32	39.09	15.09

An experiment was designed to decouple the effects of ramp time and dwell time. The effect of ramp time was studied over fixed dwell time, then the effect of dwell time was studied with a common ramp time in temperature profiles. The experimental strategy is listed in Table 2. The temperature range is from -55°C to 125°C.

Table 2. Temperature range is from -55°C to 125°C.

Case	Ramp time (min) (ramp down/ramp up)	Dwell time (min) High T dwell/low T dwell
1	3/2	15/15
2	15/15	15/15
3	3/2	3/3
4	3/2	30/30
5	15/15	30/30

Finite Element Results & Discussions

This study focuses on the bare-die FCBGA package only. The most critical solder joint is the outermost corner joint under die shadow, while the most critical interface is the package to solder interface (both derived from FEA simulation). The averaging scheme proposed by Darveaux [5, 10] is used in the calculation of per-cycle inelastic strain energy density.

Effect of Ramp Rate

In Fig. 1, the accumulated inelastic energy density (case 1 & 2 in Table 2) is plotted against time in one cycle period. The dotted lines are the temperature profiles for thermal shock and thermal cycling, respectively. The dwell time for both cases is the same (15 minutes each in low and high temperatures). Each cycle starts from ramp down, low-temperature dwell, to ramp up and high-temperature dwell. The red dots in the figure indicate the start/end point of 4 stages of a cycle for thermal shock and thermal cycling, respectively. The results clearly show that the accumulated strain energy density with shorter ramp time is much greater than that with longer ramp time. Therefore, thermal shock is predicted to impose more damage than thermal cycling on the solder joint. From Fig. 1, it can be seen that the inelastic strain energy density is primarily accumulated during the ramp portions. Larger temperature ranges of ΔT would cause more damage accumulation during the ramp portion. This confirms that ΔT is one of most significant parameters impacting solder joint reliability. There is also a very large contribution to the total strain energy density during the low-temperature dwell-time portion. However, results show that during the high-temperature dwell-time portion, the contributions are negligible. Although creep rates in general at high temperatures are several orders of magnitude higher than that at lower temperatures, the very low stress levels at high temperatures appear to negate this effect.

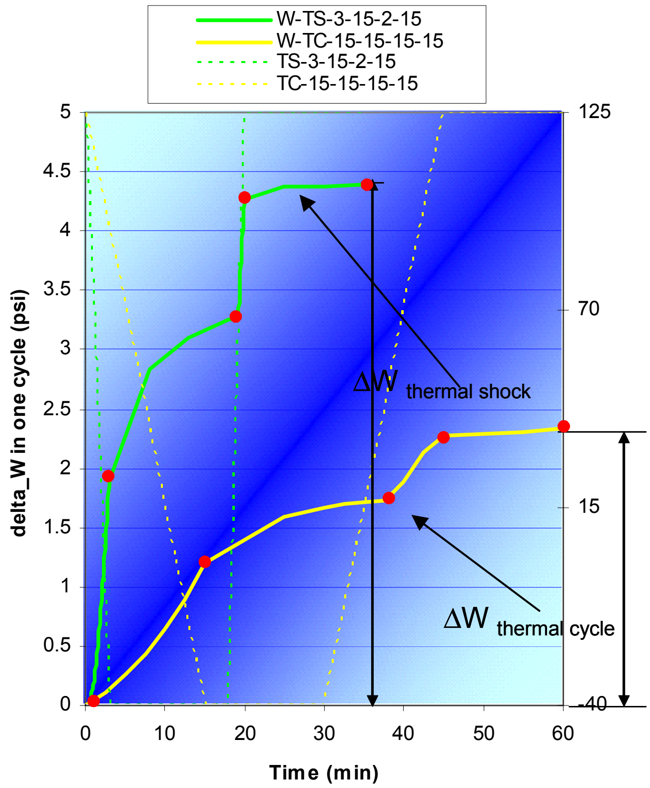

Fig. 1 Accumulated strain energy density in on cycle period for thermal shock and thermal cycling, respectively (dwell time is kept 15 minute for both cases)

Effect of Dwell Time

In Fig. 2, three different dwell times are considered (cases 1, 3, 4 in Table 1): 3 min, 15 min, and 15 min for thermal shock. The results are also compared to the thermal cycling with a 15 minute ramp time and a 15 minute dwell time. Results show that, overall, thermal shock introduces more damage to the solder joints during ramp portions than thermal cycling. Also, the accumulated strain energy density at high-temperature dwell times has almost negligible contributions to the total accumulated strain energy density. This implies that dwell times at high temperatures have insignificant contributions to the failure of solder joints during thermal shock and thermal cycling.

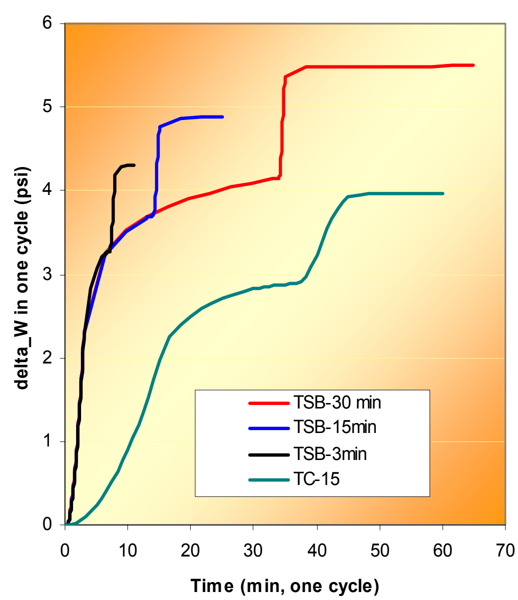

Fig. 2 Effects of dwell times (cases 1, 3, 4 & 5 in Table 2)

Fig. 3 and Fig. 4 show the percentage of strain energy density and creep strain in each stage during one cycle, indicating that the majority of damage comes from the ramp portions, not the dwell portions.

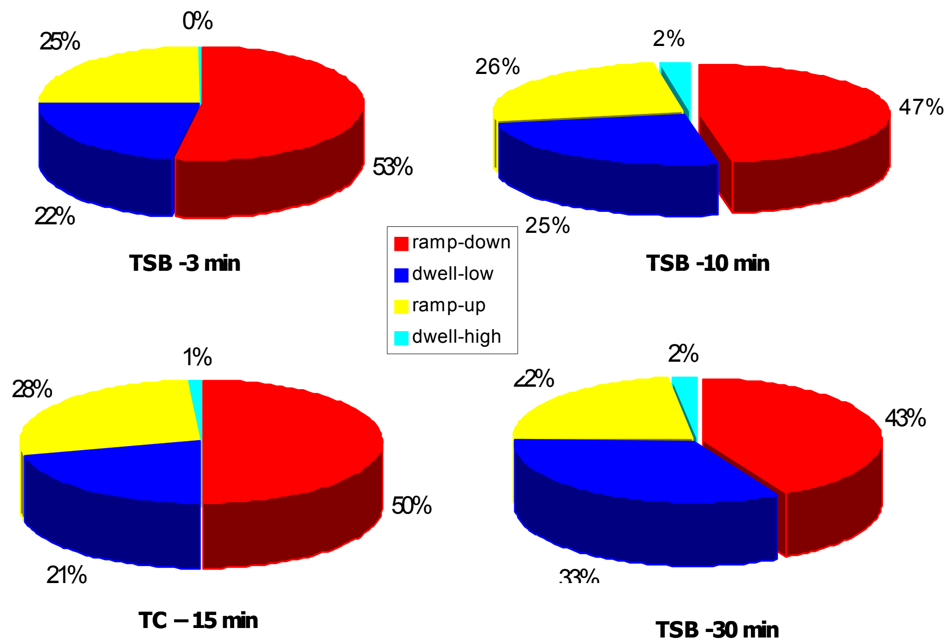

Fig 3 The percentage of the inelastic strain energy accumulated in each stage in one cycle.

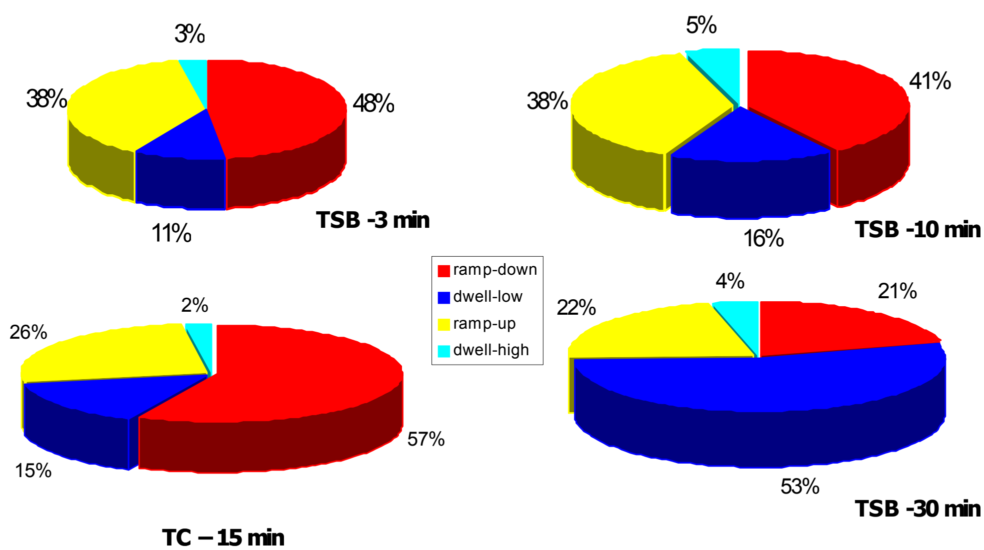

Fig 4 The percentage of the inelastic strain accumulated in each stage in one cycle.

Correlation with Experimental Study

Some of previous experimental test results on dwell time and ramp-rate effects, by Shubhada Sahasrabudhe and Eric Monroe [16], are introduced here. Fig. 5 is the probability plot for solder joint failures in BGA packages during thermal shock with different dwell times. The test data analysis revealed a strong dwell-time dependency for the onset of electrical failure, with longer dwell times driving earlier failures. A remarkable agreement between the test results in Fig, 5 and the inelastic strain energy density analysis in Fig. 2 is achieved. This indicates that the accumulated inelastic strain energy density correctly represents the effect of dwell time on accumulated damage. Fig. 6 shows the experimental results of solder-joint electrical failures under both thermal-shock and thermal-cycling conditions. Thermal shock indeed imposes more damage, and thus causes earlier failures than thermal cycling. Again, this is in good agreement with the inelastic strain energy density analysis in Fig. 3.

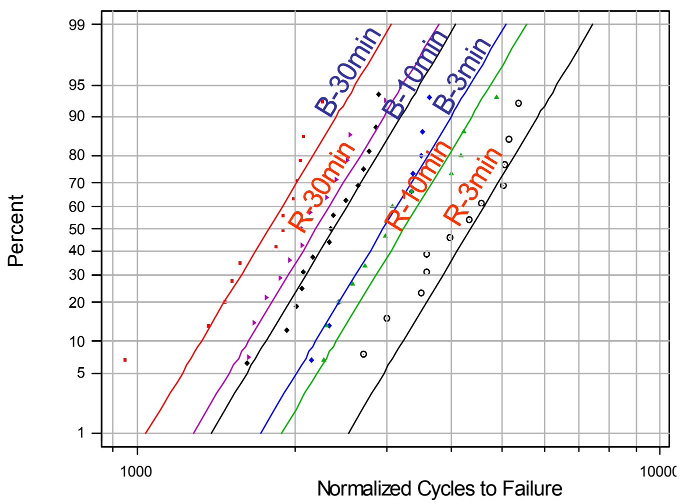

Fig. 5 Probability plots for BGA electrical failures during thermal shock with different dwell times

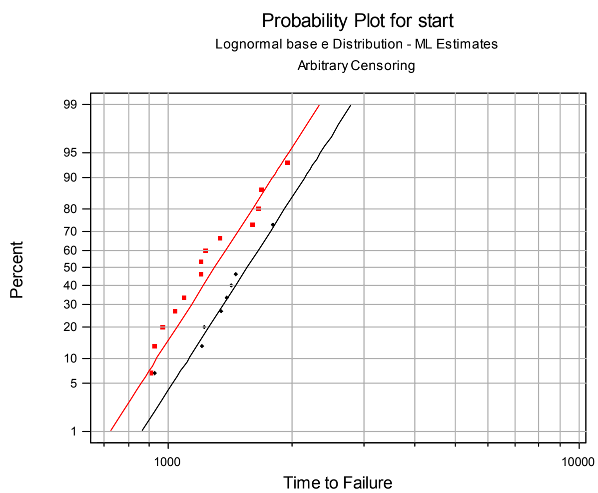

Fig. 6 Probability plots for BGA electrical failures during thermal shock and thermal cycling

Conclusions

A major challenge using ΔT-based Coffin-Mason type equations in reliability assessments of solder-joint reliability has been the lack of scalability and predictability to different package dimensions, and different material properties. In addition, the linear acceleration factors are typically assumed to extrapolate the life under use conditions. Such an approach lacks the physics-based understanding of stress acceleration and requires data from multiple testing conditions.

This study used the accumulated inelastic strain energy density as a damage parameter to relate stress conditions. A remarkable agreement on the correlation between the finite element analysis and experimental results was achieved for one case in particular. The numerical results revealed insights into solder-joint dependencies associated with ramp rate and dwell time. Thermal shock, for example, has a much faster ramp rate, and therefore imposes much more damage on the solder joints than thermal cycling. In that sense, the fatigue life decreases when frequency increases. However, a longer dwell time causes more creep in solder joint, and thus, fatigue life is significantly decreased. This implies that fatigue life actually decreases when frequency decreases. It can be concluded that frequency as a single parameter for a reliability model doesn't account the conflicting effects of ramp rate and dwell time. The finite element results also showed that the majority of damage occurs during the ramp portion, which supports the traditional ΔT-based model. Dwell time at high temperature appears to have negligible contributions to the total inelastic strain energy density.

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