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Sensitivity Analysis for the Dependence of Solder Joints Fatigue Life

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In electronic package technology, solder joint is not only used for the electrical connection and mechanical connection, but also offering the channel of heat dissipation. As chip package had developed from pin through-hole to pin surface mount, until the current no-pin ball array surface mount. Electronic package is developing in the direction of smaller ball grid array pitch, smaller chip size and more number of solder balls. The fact makes the reliability problem of solder joint become more and more outstanding. Studies have shown that 70 percent of electronic devices' failure was caused by the failure of package assembly, and the failure of solder joint is the main reason in electronic package. The main failure mechanism of solder joint is low cycle thermal fatigue, and failure reason is the coefficient of thermal expansion (CTE)'s mismatch between components and circuit boards, then the thermal stress and strain don't match in solder joint. The uncoordinated thermal strain will produce stress concentration, leading to the crack initiation and propagation, finally the solder joints' failure.

1. Introduction

There are two mainly factors considered to affect the reliability of the solder joints, which consist of the characteristics of the solder joint itself and load conditions applied to the solder joints. The characteristics of solder joint itself is related to the following factors, including the microstructure of solder alloy composition, the connection of solder, component tip and pad, the shape and size of solder joint, and the voids in the solder joints. The geometry of solder joint has a large impact on its fatigue life, and designing reasonable shape of solder joint will significantly increase its life. Since the 1990s, foreign researchers have made certain achievements in solder joints' shape prediction and design optimization. J.H.L.Pang (2001) studied the influence of temperature range on solder joints' stress, strain and thermal fatigue life, and the influence of packaging devices' geometry on solder joints' reliability. H.Reichi (2000) studied the influence of solder ball height on the life of Fixed Interconnection pattern (FIP)-Chip Scale Package (CSP) devices which were integrated on FR-4 substrate. The study of Masald Shiratori and Qiang YU (2003) showed that the two major factors affecting the reliability of solder joint were solder volume and pad diameter. With different package components as examples, Vivek Mansingh (2000) studied the solder joints' shape prediction, design and optimization of process parameters, and their impact on the solder joint fatigue life. But domestic study in this respect has not reached a certain depth; Huang Hongyan (2003) studied the influence of pad size on SMT solder joints' reliability by using finite element analysis, and considered that pad size was one of key factors which affected the solder joints' reliability. Wang Guozhong (1997) thought that the solder joints' reliability was directly related to the generalized solder joints' shape, including pad size, quality of brazing, process parameters and joint formation geometry, and stress distribution.

Previous studies have focused on the height, shape and size of solder joint itself, but simulation showed that the geometry of different package types' devices have different effects on the reliability of solder joint. So with the example of pin through-hole package devices, this paper analyzes the influence of geometries of solder joint and device on solder joints' thermal cycle fatigue life in two ways of theory and finite element

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analysis. Based on these results, influence degree of geometric parameters is obtained, providing a reference for the choice of parameters in engineer.

2. Fatigue life assessment model of solder joint

2.1 Strain analytical model

Mechanism model of fatigue failure can be divided into stress-based fatigue model, strain-based fatigue model, energy-based fatigue model and other types. Most of the solder joint fatigue model need establish the stress-strain relationship (constitutive relationship) to predict fatigue life. By contrast, the strain-based model is the most commonly used. Usually the strain is divided into the following three parts: $\Delta\gamma = \gamma_e + \gamma_p + \gamma_c$, which γ is the total shear strain, γ_e is the elastic shear strain component, γ_p is plastic shear strain component, and γ_c is creep strain component. The three components are usually intertwined, so it is difficult of strictly distinct them in practical application. Strain can be determined in a variety of ways, for simplified first-order fatigue model of lead and leadless package; it can be obtained by the formula (1) and (2).

$$\Delta\gamma = F\frac{L_D}{h}\Delta\alpha\Delta T \tag{1}$$

$$\Delta\gamma = 0.5F\frac{K_D}{\left(200psi\right)Ah}\left(\Delta\alpha_C L\Delta T - \Delta\alpha_S L\Delta T\right)^2 \tag{2}$$

Formula(1) is suitable for the solder joint of leadless package (e.g Leadless Chip Carrier (LCC)), where h is the height of solder joint, LD is the characteristic size, $\Delta\alpha$ is the difference of CTE between the material of device package and circuit board. ΔT is the difference between the maximum and minimum temperature in the thermal cycle profile, F is the correction coefficient, generally between 0.5 and 1.5.

Formula(2) is suitable for the solder joint of lead package (e.g Small Out-Line Package (SOP), Plastic Quad Flat Package (QFP))，where K_D is the stiffness of lead material(in unit of 1b/in), A is the area of solder joint(in unit of in2), h is the height of solder joint(in unit of in), α_C is the CTE of device package, α_S is the CTE of circuit board, L is half of the diagonal length of the lead(in unit of in), ΔT is the difference between the maximum and minimum temperature in the thermal cycle profile, F is the correction coefficient, generally between 0.5 and 1.5.

2.2 Strain-based fatigue life model

The model is also known as the Coffin-Manson model (as formula (3) shown), it is a widely used model of low cycle fatigue life. In the form of a power law, this model connects completely symmetrical circular plastic strain and the number of cycles to failure by two materials' constants related to temperature, the two constants are determined by experience.

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f\left(2N_f\right)^c \tag{3}$$

Where, N_f is the number of thermal cycles to failure(life); $\Delta\varepsilon_p$ is the plastic strain amplitude; ε_f is the fatigue ductility coefficient, and it is often equal to the tore fracture toughness of material when actually used, for the eutectic solder, ε_f =0.325; c is the fatigue ductility exponent, $c = -0.442 - 6\times10^{-4}T_{sj} + 1.74\times10^{-2}\ln\left(1+\frac{360}{t_H}\right)$, T_{sj} is the average circular temperature(in unit of□); t_H is the duration of high temperature(in unit of minutes).

As Coffin-Manson model only considers the plastic deformation, in order to obtain the impact of elastic deformation, the model and Basquin equation are usually combined, taking into account the impact of elastic strain and plastic strain, which is known as the total strain model.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \tag{4}$$

Where σ_f is the fatigue strength coefficient, b is the fatigue strength exponent.

3. Analysis of influence of geometric parameters on solder joints' life

With pin through-hole component as an example, this paper analyzes the influence of geometry of solder joint and device on solder joints' life. In order to simplify the derivation, the following analysis is divided into two parts, namely the influence of strain on fatigue life and influence of geometric parameters on strain. In practical applications, designers can evaluate the quantitative degree of influence of geometric parameters on fatigue life by combining two parts.

3.1 Influence of strain on fatigue life

Accelerated thermal cycling method has been widely used in experimental research and numerical simulation studies. In order to quickly assess solder joints' life, the applied temperature profile according to the working condition of the device is shown in Fig.1. Based on the profile and formula (5), the relationship of fatigue life and strain are shown in Fig.2. Here $T_{sj} = 6℃$, $t_H = 71.6$.

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{0.65}\right)^{-2.42} \tag{5}$$

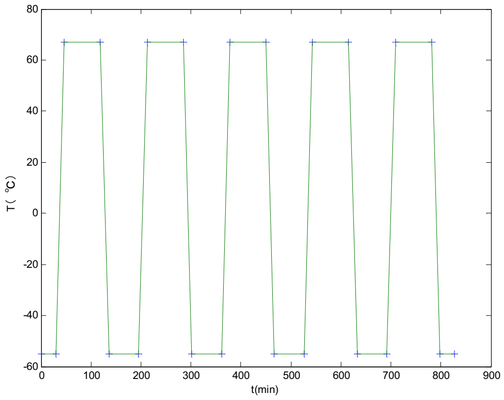


Fig.1 temperature profile

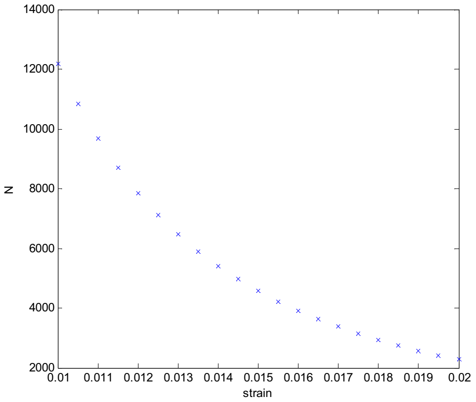


Fig.2 relationship of cycles and strain

As Fig.2 shows, the life decreases as the strain increases, so the influence of geometric parameters on the life can be analyzed by strain as a contact.

3.2 Influence of geometric parameters on strain

Because the device is lead packaged, the relationship of strain and geometry satisfies the equation (2), which diagonal length of the lead can be calculated by solder joint height and pin diameter, satisfying the relationship $L = \frac{\sqrt{h^2 + r^2}}{2}$, $A = R^2 \times \frac{\pi}{4} \times \frac{2}{3}$, so the relationship of geometric parameters and strain meets the formula (6).

$$\Delta\gamma = 0.5F \frac{K_D}{200(psi)R^2 \times \frac{\pi}{4} \times \frac{2}{3} \times h}((\Delta\alpha_C - \Delta\alpha_S) \times \Delta T \times \sqrt{h^2 + r^2})^2 \tag{6}$$

Materials used in the analysis process and the related constants are shown in Table1.

Table 1. Material constants

Material	coefficient of thermal expansion(CTE) (ppm/℃)	Stiffness (lb/in)
℃metal	$23.4*10^{-6}$	/
FR-4	$19.1*10^{-6}$	/
C197	/	75.1

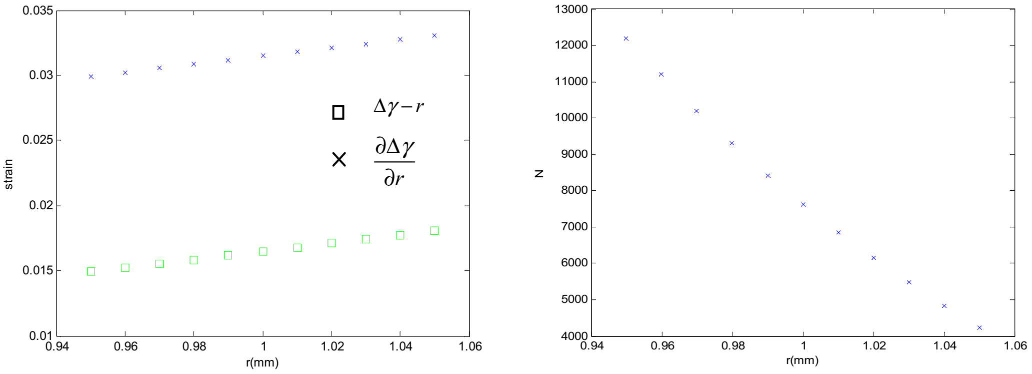
The formula (7) can be obtained by substituting the material constants into formula (6):

$$\Delta\gamma = 0.5F\frac{75.1}{200(psi)R^{2}\times\frac{\pi}{4}\times\frac{2}{3}\times h}(4.3\times\Delta T\times\sqrt{h^{2}+r^{2}})^{2} \tag{7}$$

By referring device handbooks, IPC package standard and circuit board's designed document, the conventional geometry of device is as follows: h=1.5mm,r=1mm,R=2.3mm. These values can be used to analyze the influence of a single geometric parameter on strain. First we analyze the changing trend and sensitivity of strain with pin diameter, pad diameter, and solder joint height by choosing one parameter as a variable value and setting the other parameters conventional geometry. Then we analyze the results of cycles to failure with changing of pin diameter, pad diameter, drill size, standoff height, solder joint height and ratio of pin diameter and pad diameter.

Pin diameter

Based on engineering experience and device handbooks, the range of $0.95mm \le r \le 1.05mm$ is selected. By choosing pin diameter as a variable value and setting the other parameters conventional geometry, the relationship of strain and pin diameter is $\frac{\partial\Delta\gamma}{\partial r}=\frac{0.254r}{R^{2}h}$, as Fig.3 (a) shown. According to the results of finite element analysis, the relationship of the number of thermal cycles to failure and pin diameter is shown in Fig3 (b).



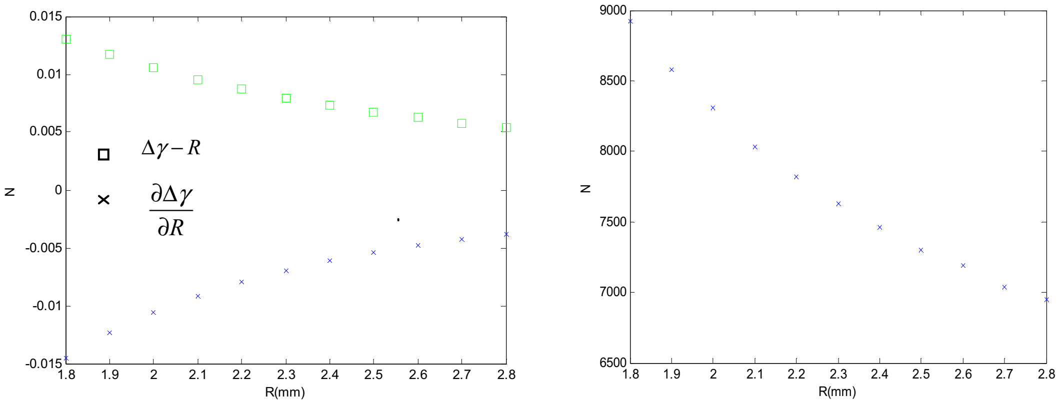
(a) *(b)*

Fig.3 Relationship of strain, cycles and pin diameter

The strain and its sensitivity to pin diameter increase as pin diameter increase, so the fatigue life will decrease with the increase of pin diameter.

Pad diameter

Based on engineering experience and circuit board's designed document, the range of $1.8mm \le R \le 2.8mm$ is selected. By choosing pad diameter as a variable value and setting the other parameters conventional geometry, the relationship of strain and pad diameter is $\frac{\partial\Delta\gamma}{\partial R}=-0.127(\frac{r^{2}}{R^{3}h}+\frac{h}{R^{3}})$, as Fig.4 (a) shown. According to the results of simulation, the relationship of the number of thermal cycles to failure and pad diameter is shown in Fig.4 (b).



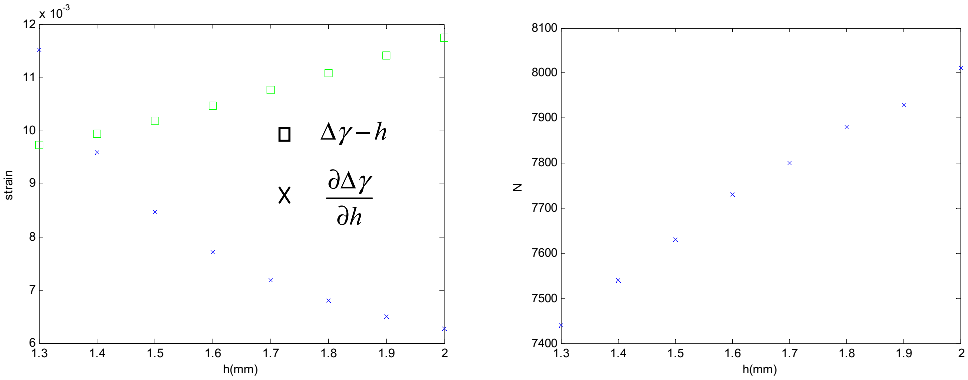
(a) *(b)*

Fig.4 Relationship of strain, cycles and pad diameter

The strain decreases as pad diameter increases, but its sensitivity to pad diameter increases as pad diameter increases. These results are inconsistent with results calculated by the finite element analysis, so we suspect that the pad diameter may not be considered as a separate factor. Thus later in the paper we discuss the influence of ratio of pin diameter and pad diameter on the fatigue life.

Solder joint height

Based on the engineering experience, the range of $1.3mm \le h \le 2mm$ is selected. By choosing solder joint height as a variable value and setting the other parameters conventional geometry, the relationship of strain and pad diameter is $\frac{\partial \Delta\gamma}{\partial h} = -0.005(\frac{r^2}{R^2h^2}+1)$,as Fig.5(a) shown. According to the results of simulation, the relationship of the number of thermal cycles to failure and solder joint height is shown in Fig.5 (b).



(a) *(b)*

Fig.5 Relationship of strain cycles and solder joint height

The strain decreases as solder joint height increases, but its sensitivity to solder joint height increases as solder joint height increases. So the fatigue life will increase with the increase of solder joint height.

Ratio of pin diameter and pad diameter

Based on engineering experience, the range of $0.95/2.4 \le ratio \le 1.05/2.2$ is selected. According to the results of simulation, the relationship of the number of thermal cycles to failure, ratio of pin diameter and pad diameter and different pad diameter is shown in Fig.6.

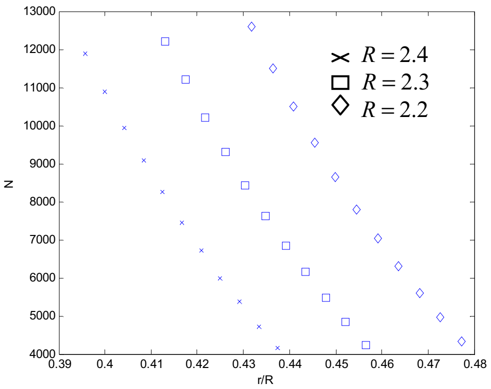


Fig.6 relationship of ratio of pin diameter and pad diameter and cycles

Figure6 shows that the fatigue life decreases with the increase of ratio of pin diameter and pad diameter, in the condition of the same ratio, fatigue life increases as pad diameter increases.

4. Conclusions

Based on the influence of geometry of solder joint and device on solder joints' fatigue life obtained from analytical model, these results show that in order to obtain higher reliability of solder joints, designers should appropriately reduce pin diameter, ratio of pin diameter and pad diameter, and increase solder joint height. According to the sensitivity of fatigue life to geometric parameters obtained from analytical model, these results show that the sensitivity of fatigue life to pin diameter is the highest, the designers should choose appropriate pin diameter in order to increase the fatigue of solder joint.

References

Huang Hongyan, Zhou Dejian and Wu Zhaohua (2003), "Effect of the solder pad size on the reliability of the solder joint", Journal of Guilin Institute of Electronic Technology, Vol. 23 No.1, pp.34-37

Kim D G, Kim J W and Juang S B (2006), "Evaluation of solder joint reliability in flip chip package under thermal shock test", Thin Solid Films, Vol. 504 No.1-2, pp.426-430

Kirstern W (1999), "Impact of FEM simulation on reliability improvement of package", Microelectron Reliab,Vol.39, pp.1079-1088

Lau J.H (1991), "Modern Approaches to Fatigue Life Prediction of SMT Solder Joints", Solder Joint Reliability:Theory and Application

Mansingh Jim Heckman and Ahnler Syed (2000), "Solder Joint Fatigue Life of Fine Pitch BGA Impact of Design and Material Choices", Microelectronics Reliability, Vol. 1 No.40, pp.1117-1127

Pang J H L, Chong D Y R and Low T H (2001), "Thermal cycling analysis of Flip-Chip solder joint reliability", IEEE Trans Compon Packg Technol, Vol. 24 No.4, pp.705-712

Qiang Yu, Masaki Shiratori and Yoich Ohshima (2003), "A study of the effects of BGA Solder Geometry on Fatigue Life and Reliability Assessment", IEEE Inter Society Conference on Thermal Phenomena, pp.229-235

Reichl H, Schubert A and Topper M (2000), "Reliability of flip chip and chip size package", Microelectron Reliab, Vol. 40, pp.1243-1254

Wang Guozhong, Wang Chunqing and Qian Yiyu (1997), "Prediction of Stand-off Height Between Chip Component and Substrate and its Effects on Three-dimensional Solder Joint Geometry", Electronics Process Technology, Vol. 18 No.2, pp.60-62