Springer

Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 22 (2008) 683~688

www.springerlink.com/content/1738-494x

Reliability estimation of solder joints under thermal fatigue with varying parameters by using FORM and MCS

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(Manuscript Received August 24, 2007; Revised January 16, 2008; Accepted January 17, 2008)

Abstract

One of major reasons for the failure of solder joints is thermal fatigue. Also, the failure of solder joints under thermal fatigue loading is influenced by varying boundary conditions such as the material of the solder joint, the materials of substrates(related to the difference in CTE), the height of solder, the distance of the solder joint from the neutral point (DNP), the temperature variation and the dwell time. In this paper, first, the experimental results obtained from thermal fatigue test are compared to the outcomes from theoretical thermal fatigue life equations. Second, the effects of varying boundary conditions on the failure probability of the solder joint are studied by using probabilistic methods such as the first order reliability method (FORM) and Monte Carlo simulation (MCS).

Keywords: FORM; Failure life; Failure Probability; MCS; Solder Joints

1. Introduction

Soldering is the most popular joining technology in the electronic industry. The successful estimation of lifetime of a solder joint highly depends on the degree of accurate modeling of the stress and strain related to the strength of the solder joint. The main cause of failure in solder joints is considered to be thermo-mechanical stresses, caused by differences in the coefficient of thermal expansion (CTE) between the chip and the substrate. Also, the package variables including the die size, the package size, the ball count, the pitch, the mold compound and the substrate material affect the failure life of solder joints [1]. However, it is not easy to consider all of the variables. In this study, the material of a solder joint, the materials of substrates, the height of solder, the distance of the solder joint from the neutral point (DNP), the temperature variation and the dwell time were considered. Furthermore, experimental results obtained from thermal fatigue tests were compared to that from theoretical fatigue failure life equations. The effects of varying boundary conditions on the failure probability of the solder joint were also studied by using probabilistic approach methods such as the first order reliability method (FORM) and Monte Carlo simulation (MCS).

2. Fatigue failure models

A generalized fatigue damage law for metals has been proposed on the basis of cumulative stored visco-plastic strain energy density. The cyclic shear fatigue life is related to in a stabilized fatigue cycle by the equation [2]:

$$\overline{N}_f = \frac{1}{2}\left[\frac{\Delta W}{W_f^{'}}\right]^{\frac{1}{c}} \tag{1}$$

Where c = fatigue ductility exponent

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DOI 10.1007/ s12206-008-0117-2

$\overline{N}_f$ = cycles-to-failure
$W_f^{'}$ = intercept energy term, a material constant
ΔW = viscoplastic strain energy density per cycle

The following well-known Manson-Coffin plastic strain-fatigue life relationship is a special stress limited case of this generalized fatigue damage function.

$$\overline{N}_f = \frac{1}{2}\left[\frac{\Delta\gamma}{2\varepsilon_f^{'}}\right]^{\frac{1}{c}} \tag{2}$$

Where $\Delta\gamma$ = cyclic shear strain range
$\varepsilon_f^{'}$ = fatigue ductility coefficient

Where, c and $2\varepsilon_f^{'}$ are defined below, respectively:

$$2\varepsilon_f^{'} \approx 0.65 \tag{3}$$

$$c = -0.442 \times -6 \times 10^{-4} T_m + 1.74 \times 10^{-2} \ln\left(1 + \frac{360}{t_D}\right) \tag{4}$$

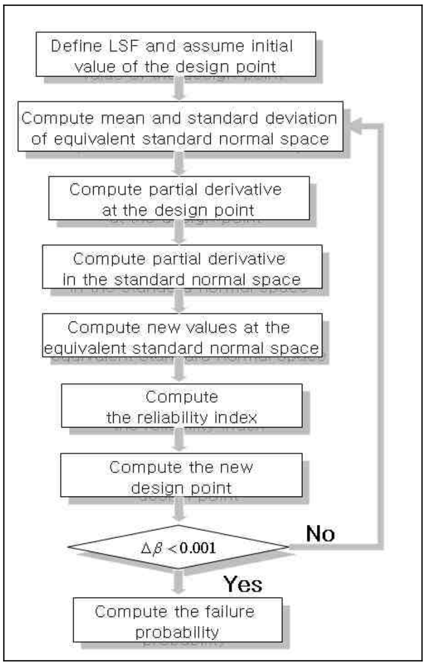

Fig. 1. Processing of computing the reliability index.

Where T_m = mean cyclic solder joint temperature
t_D = half-cycle dwell time (min)

The cyclic strain range is given by

$$\Delta\gamma = F \cdot \frac{L_D}{h} \cdot \Delta\alpha \cdot \Delta T \tag{5}$$

Where F = empirical "nonideal" factor indicative of deviations of real solder joints from idealizing assumptions and accounting for secondary and frequently untractable effects
$F \approx 1.27$ for column-like leadless solder attachments, $F \approx 1.0$ for solder attachments utilizing compliant leads
L_D = Distance of the solder joint from the Neutral Point (DNP)
h = solder joint height, solder diameter
$\Delta\alpha$ = absolute difference in coefficients of thermal expansion of solder joint and substrate, ΔCTE
ΔT = cyclic temperature swing.

Thus, from combining (2), and (5), the cyclic life of surface mount solder attachment is obtained as [2].

$$\overline{N}_f = \frac{1}{2}\left[F \cdot \frac{L_D \cdot \Delta\alpha \cdot \Delta T}{2\varepsilon_f^{'} \cdot h}\right]^{\frac{1}{c}} \tag{6}$$

3. Failure probability models

The failure probability is calculated by using the FORM, which is one of the methods utilizing a reliability index. The FORM is denoted from the fact that it is based on a first-order Taylor series approximation of the Limit State Function (LSF) [3], which is defined as:

$$Z = R - L \tag{7}$$

Where R is the resistance normal variable, and L is the load normal variable. Assuming that R and L are statistically independent normal-distributed random variables, the variable will also be normal-distributed. The event of failure occurs, when $R < L$ (i.e. $Z < 0$).

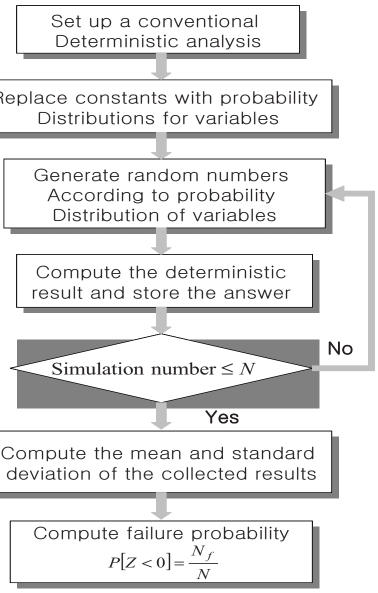

Fig. 2. Processing of computing the failure probability using the MCS.

The failure probability is given as below.

$$PF = P[Z<0] = \int_{-\infty}^{0} \frac{1}{\sigma_Z\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right\} dZ$$
$$= \int_{-\infty}^{-\beta} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{U^2}{2}\right\} dU = \Phi(-\beta) \qquad (8)$$

Where, μ_Z and σ_Z are the mean and standard deviation of the variable Z, respectively. And β is the reliability index. Rackwitz and Fiessler proposed a method to estimate the reliability index using the procedure shown in Fig. 1 [4, 5]. The MCS technique is used to check the accuracy of the results out of the FORM.

Most engineering MCSs are usually performed by using the steps shown in Fig. 2 [4].

4. The standard of failure estimation

The failure probability of the solder joint is affected by varying boundary conditions, and the LSF include

Table 1. Random variables and parameters used in the case study.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
L_D (DNP) (m)	0.00735	0.00735	0.0176	0.0176	0.0106	0.0106	0.0092	0.0092
Solder Material	Sn4Ag0.5Cu	Sn4Ag0.5Cu	Sn4Ag0.5Cu	63SnPb	63SnPb	63SnPb	63SnPb	63SnPb
Substrate Material	BT	BT	FR4	FR4	FR4	FR4	FR4	FR4
$\Delta\alpha$ (ppm/$^\circ C$)	7.5	7.5	4.5	7.6	7.6	7.6	7.6	7.6
ΔT ($^\circ C$)	180	100	165	165	165	165	165	165
h (m)	0.00035	0.00035	0.00075	0.00075	0.000508	0.000508	0.000406	0.000508
c	-0.40699	-0.41599	-0.41149	-0.41149	-0.41149	-0.40774	-0.41149	-0.41149
Dwell Time(min)	15	15	15	15	15	12	15	15
Failure life of equation (cycles)	611	2154	1278	996	1228	1358	1005	1733
Failure life of test (cycles)	620	1170	1436	722	1305	1320	1500	1100

Table 2. C.O.V of varying boundary conditions.

	F	L_D	$\Delta\alpha$	ΔT	h	c
C.O.V	0.001	0.004	0.005	0.01	0.004	0.001

ing varying boundary conditions may be defined to estimate the influence of boundary conditions on the failure probability accordingly.

In this paper, the modified Manson-Coffin plastic strain-fatigue life relationship is used to formulate the LSF given as below with $\overline{N}_f$ as the resistance variable and N_s as the load variable.

$$Z = \overline{N}_f - N_S = \frac{1}{2}\left[F \cdot \frac{L_D \cdot \Delta\alpha \cdot \Delta T}{2\varepsilon_f^{'} \cdot h}\right]^{\frac{1}{c}} - N_S \qquad (9)$$

Where, N_s is the specified fatigue cycles that is the noted number of fatigue cycles undergone at system or structure.

5. Case study

For estimating the reliability of solder joints, the results of a thermal fatigue test of eight samples are utilized in this study. Each sample has difference variables. The random variables in Table 1 have been utilized to estimate the failure probability of the solder joint. The data in Table 1 are obtained from the experiment we have collected from other papers. In Table 1, the failure life of equation is results obtained using Eq. (6) and the failure life of test is results obtained from other papers. The standard of failure in this study is defined as the first failure life cycle [1, 6-10].

The C.O.Vs of varying boundary conditions listed in Table 2 are taken from some reference [9]. The C.O.V is defined as below with the standard deviation, σ_Z and the mean, μ_Z

$$C.O.V = \frac{\sigma_Z}{\mu_Z} \qquad (10)$$

5. Results and discussions

In this paper, we formulate the limit state function like Eq. (9) to investigate the reliability of solder joints according to varying various random variables. We calculate the failure probability with changing of the specified fatigue cycles, N_s, and the data in Table 1 are applied to the other variables of Eq. (9) to calculate the failure probability. We obtain and show the results the relationship between failure probability and number of cycles.

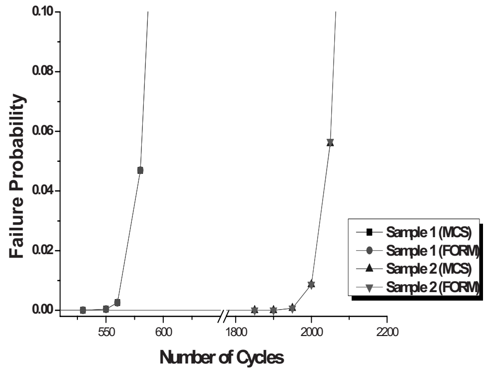

Fig. 3. The relationship between the failure probability of the solder joint and cyclic temperature swing.

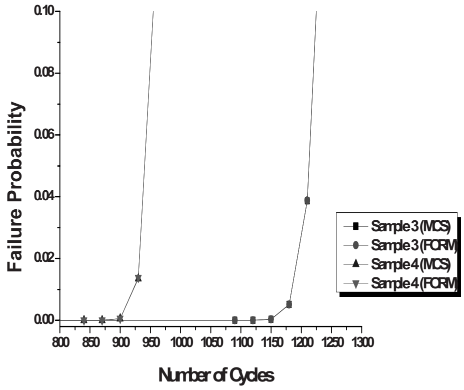

Fig. 4. Relationship between the failure probability and solder material (difference in CTE).

Fig. 3 shows the relationship between the failure probability of the solder joint and the cyclic temperature swing. It is confirmed that the failure probability increases with increase of the cyclic temperature swing.

Fig. 4 shows that the relationship between the failure probability and the difference in CTE for solder material. It is found that the failure probability increases with increase of the difference in CTE. The reliability of lead-free solder joint (Sn4Ag0.5Cu) is estimated better than that of lead solder joint(63SnPb).

Fig. 5 shows the relationship between the failure probability and the dwell time: the failure probability increases with increase of the dwell time.

Fig. 6 shows the relationship between the failure probability and the solder joint height. For this case, it

Table 3. Difference ratio of the failure probabilities obtained by using the FORM and the MCS: difference ratio=100 ×(FORM-MCS)/ FORM.

	Failure life(cycles)	MCS	FORM	Difference rate [%]
Sample 1	580	0.04691	0.04693	0.0426
Sample 2	2050	0.05594	0.05656	1.0962
Sample 3	1210	0.03866	0.03884	0.4634
Sample 4	930	0.01351	0.01383	2.3138
Sample 5	1150	0.01722	0.01726	0.2317
Sample 6	1250	0.04232	0.4246	0.3297
Sample 7	950	0.03433	0.3465	0.9235
Sample 8	1650	0.05764	0.0579	0.4491

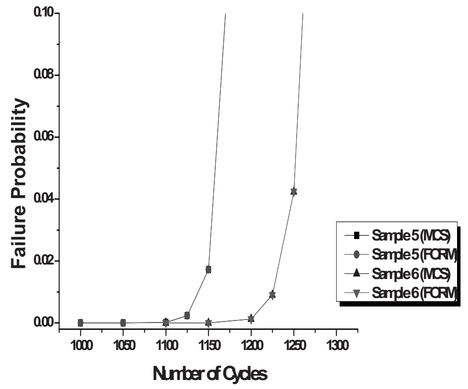

Fig. 5. Relationship between the failure probability and dwell time.

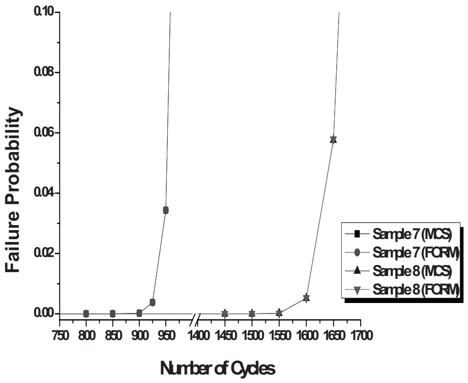

Fig. 6. Relationship between the failure probability and solder joint height.

is noted that the relationship obtained by using the failure life of equation and the one estimated from experimental failure life test do not agree with each other. Samples 7 and 8 have the same variables except for the die size and the solder ball diameter [1]. We speculate on the mismatch in Fig. 6 as the exclusion of the die size in the fatigue life equation.

Table 3 shows the difference ratio of the failure probabilities obtained by using the FORM and the MCS. The failure life in Table 3 is the specified failure life, N_s, is the value, when the failure probability from FORM and MCS shows the values listed in Table 3. We obtain these results using the values listed in Table 1. It is recognized that the results by the FORM and the MCS are almost the same. The difference ratios are found to be less than 2.3 %.

6. Conclusions

In this paper, the reliability of solder joints under varying conditions is estimated by FORM and MCS. FORM is utilized to extract useful technical information in carrying out effective failure control. The results obtained by the FORM are verified by comparing to those from the MCS. The following results are obtained:

(1) The failure probability increases with increases in number of thermal fatigue cycles.

(2) The failure probability decreases with decrease in the cyclic temperature swing, the difference in CTE and dwell time.

(3) The failure life determined by the theoretical fatigue life equation is found to be similar to the one obtained by the experimental test except for the case of the different height of the solder joint.

(4) The FORM is found to be an efficient technique to estimate the failure probability of the solder joint under the temperature boundary condition. The results out of the FORM are verified by comparing with those from the MCS.

Acknowledgment

This work was supported by Brain Korea 21 project in 2007. The main part of this paper was presented at WCE2007 held in London, England on July 02~04, 2007.

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