Response Prediction and Verification for PCB with Package due to Thermal and Random Vibration Coupling Effects

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ABSTRACT

The printed circuit board (PCB) subject to vibration and thermal couple loading is of great interest. This work presents both theoretical analysis and experimental verification for the PCB in heating condition subject to random vibration. The designed heating pad is used as the heating source attached to the package on PCB by providing constant temperature inputs. The calibrated finite element model of PCB in fixture condition is employed to perform thermal analysis for the PCB subjected to the fixed high temperature at the package surface. The thermal response of the PCB can be determined, and thus the spectrum response analysis of the PCB including the thermal effect for random excitation according to JEDEC specification is carried out. The temperature distribution over the PCB in heating condition is monitored by the digital infrared thermography and compared with that of finite element analysis (FEA). The acceleration spectral responses on the PCB during random vibration test with thermal effect are also recorded. Results show that the predicted temperature distribution for the heated PCB and acceleration response due to thermal and random vibration compound loadings agree reasonably between the FEA and experiments. The stress fields on the PCB subject to the thermal input and random vibration excitation can then be obtained and evaluated for its possible fatigue failures due to the compound loading effects. This work presents the analytical solutions via the commercial FE code for the PCB subject to compound loadings for thermal input and random vibration excitation. The predicted results are well validated by comparing with experiments. The developed methodology will be beneficial for further study of PCB and its package reliability in considering both thermal and vibration inputs simultaneously.

Keywords: PCB, response prediction, thermal analysis, random vibration

1. Introduction

In electronic industry, the printed circuit boards (PCBs) become smaller. Beside the concern of thermal effect, the vibration induced failures during assembly, transportation and in use must also be considered in design. The coupling loadings of thermal and vibration effects are critical issues. This work aims to study the compound loadings on the PCB. Both theoretical analysis and experimental measurement will be carried out to obtain the equivalent PCB finite element (FE) model that is further adopted to perform random vibration analysis including the thermal effect so as to predict the PCB failures due to thermal and random vibration coupling effects.

Gibson [1] applied experimental modal analysis (EMA) technique to determine mechanical properties of PCB materials in various kinds of environments. Liou *et al*. [2] investigated the structure subject to random vibration loadings and predicted the fatigue life by theoretical and experimental approaches.

Joint Electronic Device Engineering Council (JEDEC) specified the drop test and random vibration test standards. That provided with the guidelines for PCBs testing for the concerns of failures due to shock and vibration. Lai *et al*. [3] used the standard to test the PCB. Results showed that the junction between the solder balls and packages is the common failure location.

Different contents of materials for the solders will alter the damage levels. Perkins *et al*. [4] studied the solder failures of ceramic column grid array (CCGA) type of packages. They used finite element analysis (FEA) to model the PCB, in particular the beam elements were used to construct the solder balls for failure analysis. In experiments, two sides of the PCB were fixed and excited to observe the failure location of solder balls. The solder balls failures occurred near the two edges of packages and the junction between the solder ball and PCB. This may be due to the lack of material strength in solder balls and the adhesion strength on the board.

The rapid cyclic thermal effect can reveal early defects for electronic products, so the cyclic thermal test is performed to improve their quality and functions. Wang *et al*. [5] adopted FEA to study the thermal fatigue reliability in accelerating cyclic thermal tests for package structures. The significant factors influencing the thermal fatigue are the substrate thickness, chip thickness and solder ball height.

Preview works [6-8] by the authors investigated the PCB subject to random vibration loading for the PCB with single and multiple chips. The coarse and refined FE models of the PCB with packages were evaluated for vibrating tests. The stress field of the PCB due to the added heat source was studied and verified by experiments. Wang *et al*. [9] applied the heating pad as the heat source on the package while the PCB was in free boundary. The temperature distribution of the PCB was analyzed and validated by experimental observation very well. Wang *et al*. [10] conducted both FEA and experimental modal analysis (EMA) on the PCB with packages in the free and fixed boundaries, respectively, to validate the FE model of the PCB by the comparison of modal parameters from FEA and EMA.

This paper adopts the verified PCB FE model [10] and summarizes the results of model verification to obtain the equivalent FE model of the PCB with the thermal input, i.e. the constant temperature in the heating pad. The spectrum response analysis with thermal effect is performed for random excitation to obtain the PCB acceleration power spectral density (PSD) function. The experiments for the random vibration tests are also carried out to obtain the corresponding PSD response. The root mean square (rms) acceleration response from both experiments and analysis can then be calculated and matched each others reasonably. The further analysis on the possible fatigue failure is also presented to discuss the effects due to thermal and random vibration loadings.

2. Calibration of FE model of PCB with Heating Pad

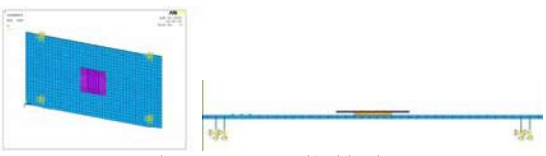
The PCB with one package is considered. The heating pad with shim that is used and adhered onto the top of the package can maintain constant temperature with DC current inputs. In this work, the heating pad is provided with 10V that can have the heating pad in 75℃. This section will show the model verification procedure to calibrate the FE model for the PCB with heating pad, in particular subject to the constant temperature, in fixed boundary revealed to natural or free convection conditions in room temperature.

2.1 FE model

The analysis objective is to obtain the modal parameters of the PCB subject to the steady thermal loading, i.e. the constant temperature in the heating pad, while the PCB is in room temperature with natural convection. The solution is carried out in two stages. First, the thermal field analysis is performed to determine the temperature distributions. Second, the thermal FE model is transformed to the structural field so as to perform modal analysis for obtaining structural modal parameters.

Figure 1 shows the FE model for the PCB with heating pad in fixed boundary established by ANSYS. In the first stage, the hexahedral solid conduction element (SOLID70) is adopted to construct the heating pad, package and PCB by neglecting details of the chip, substrate and solder balls for preliminary study. The spring elements (COMBIN14) are used to simulate the fixed boundary at the four corners. The mass elements (MASS21) are also applied to where the accelerometers applied in experiments in order to be consisted with the real situation. The heating pad with 75℃ is assumed. All other surfaces are specified as natural convection with surrounding temperature 27℃ and film coefficient 50 W/m^2℃ that is calibrated in previous work [9] for the PCB in free boundary.

Once the temperature distributions are determined, the structural field analysis is then conducted. The hexahedral solid element (SOLID45) is adopted to construct the heating pad, package and PCB. For modal analysis, only the fixed boundaries are specified with zero displacements and the temperature distributions are incorporated into the model to account the thermal effects. The thermal deformation is first calculated and with the pre-stress effect turned on for structural modal analysis to obtain the natural frequencies and mode shapes of the PCB in steady state of thermal input. For harmonic response analysis to determine the frequency response function (FRF), the unit force is applied at the location corresponding to the experiments.



(a) top view (b) side view

Figure 1. Finite element model for the PCB with heating pad in fixed boundary

Figure 2. Experimental setup for modal testing of PCB

2.2 EMA for the PCB

Figure 2 shows the experimental setup for structural modal testing or experimental modal analysis (EMA) for the PCB. The mini impact hammer is used and roving along the test points, while the accelerometer is fixed at the corner of the PCB to measure the system FRFs. The ME'scopeVES, a curve-fitting software, is adopted to determine the experimental modal parameters, including natural frequencies, mode shapes and damping ratios.

2.3 Model verification for the PCB with heating pad (75℃)

In this section, the model verification results will be shown to calibrate the FE model of the PCB by observing modal characteristics with steady thermal loadings. Figures 3 and 4 show the thermal field results. Figure 3(b) is the temperature distribution image captured by the digital infrared thermography (DIT). Figure 3(c) shows the temperature curves matching very well for both the FEA and experiment along the path as revealed in Figure 3(a). Figure 4 show the von Misses and principal stress distributions for the PCB.

Figure 5 shows the comparison of FRFs obtained from the experimental, synthesized and FEA. The synthesized FRF agrees very well with the experimental one. This indicates the success in curve-fitting procedures. One can also see that the theoretical FRF fits the experimental ones satisfactory within 1000Hz frequency range. Therefore, the FE model is basically equivalent to the practical structure.

In further examination on the modal parameters, Table 1 summarizes the comparison of modal parameters between the FEA and EMA for the PCB with steady thermal input, i.e. 75℃ in the heating pad. From Table 1(a), the natural frequency errors are within ±4%, and the modal damping ratios are also shown with the accumulative averaged damping ratio 0.666 that is applied to simulate the response prediction for obtaining FRFs and simulating random vibration excitation in next section. Table 1(b) also shows the first four mode shapes comparison. Except the fourth mode which MAC (modal assurance criterion) value is 0.67, the others are above 0.9. For MAC value, that is the correlation index between two vectors, higher the MAC values close to 1 indicates the good agreement between the experimental and theoretical mode shapes. The match of modal parameters obtained from FEA and EMA indicates the success of model verification.

3. PCB Response due to Thermal and Random Vibration Loadings

In Section 2, the PCB FE model subject to the steady thermal loading, i.e. the heating pad with constant temperature and all surfaces with natural convection boundary, is well calibrated by comparison of modal characteristics. The validated FE model will be used to perform random excitation simulation in conjunction with the JEDEC vibration test specification [11]. Figure 6 shows the random vibration test spectra for different levels, in particular Level D is considered in this work.

3.1 FE model

The calibrated FE model for the PCB is adopted. The fixed points at the bottom of the spring elements are specified as the base excitation with the acceleration spectrum as shown in Figure 6 for Level D. The spectrum response analysis is performed with the temperature distribution input obtained from the thermal field analysis and

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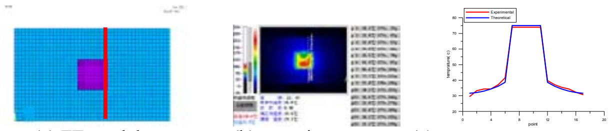
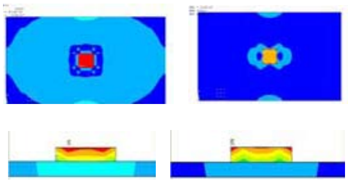
pre-stress effect turned on. The acceleration power spectral density (PSD) function on the PCB can then be calculated and compared with the experiments.



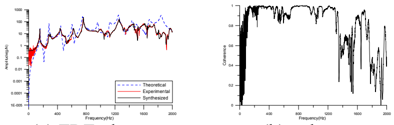
(a) FE model (b) experiments (c) temperature curve

Figure 3. Comparison of temperature between FEA and experiments



(a)von Misses stress (max. 14.3 MPa) (b) principal stress (max.16.2 MPa)

Figure 4. Stress distributions for the PCB in steady thermal input



(a) FRF plots (b) coherence

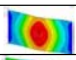
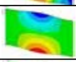
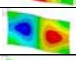
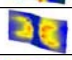
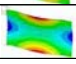
Figure 5. Comparison of FRFs among experimental, synthesized and FEA

Table 1. Comparison of modal parameters for the PCB with steady thermal input (75℃)

(a) natural frequencies and damping ratios

MODE	FEA(HZ)	EMA(HZ)	ERROR (%)	DAMPING RATIO (%)	ACCUMULATIVE AVERAGED (%)
1	158.04	152.5	3.60	0.66	0.66
2	281.1	280.49	0.19	1.218	0.939
3	445.16	436.13	2.04	1.271	1.049
4	512.96	509.23	0.70	0.939	1.022
5	595.8	-	-	1.047	1.027
6	603.62	622.84	-3.11	0.315	0.908
7	748.24	760.37	-1.62	0.42	0.839
8	957.95	1049.5	-8.74	0.302	0.772
9	968.5	-	-	0.473	0.738
10	1127.3	1257.2	-10.37	0.015	0.666

(b) mode shapes

MODE	FEA	EMA	MAC
1			0.93
2			0.91
3			0.95
4			0.67

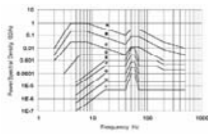


Figure 6. Random vibration test specifications for JESD22-B103-B [11]

3.2 Experiments

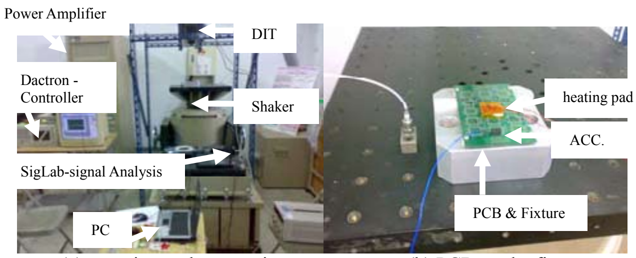
Figure 7(a) and 7(b) shows the experimental test equipments and the PCB on the fixture, respectively. Five measurement locations on the PCB are revealed on Figure 7(c). The vibration testing machine is KD-9363EM-600F2K-50N120 made by King-Design Corp. The DIT is also placed on the top to monitor the temperature distributions during tests. The accelerometer is mounted on the PCB at different locations to measure the acceleration PSDs for further comparison with the analytical solutions.

3.3 Response predictions for the PCB with heating pad (75℃)

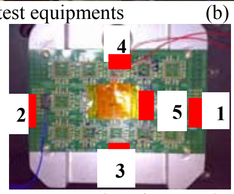
Figure 8(b) shows the monitored temperature distributions during vibration testing. There are three temperature curves in Figure 8(c). The experimental-random and fix are the PCB with and without random excitation, respectively. Only a slight difference observed indicates the thermal boundary conditions for the PCB about the same. The theoretical prediction of temperature also matches very well with the experiments.

Table 2 show the comparison of acceleration PSD obtained from experiments and FEA at different locations. The PSD curves generally agree each others except some discrepancy of peak levels at resonances. The acceleration rms values calculated from experiments and FEA are also shown and revealed reasonable agreement, though the absolute values might differ. Generally speaking, the FEA for spectrum response of the PCB subject to thermal and random excitation compound loadings is well simulated.

Table 3 shows the prediction of response distributions for the PCB with thermal input and Level D random vibration loadings in the first three resonance frequencies. Since the first resonance at 152 Hz dominates the response as seen in Table 2, two critical points for the von Misses stress in the first resonance response as indicated in Table 3 are examined. Table 4 shows the prediction of stress PSD, rms values and ranges for the PCB at the two critical locations. For random vibration test, the averaged response is zero, so the rms value is just the same as the standard deviation. For the assumption of Gaussian or normal distribution as revealed in Figure 8, there are over 99.7% samples within ± three times of standard deviations. Therefore, the stress ranges can be interpreted as the three times of the rms values as revealed in Table 4. The maximum and minimum stresses can be further applied to Goodman line for fatigue evaluation. Figure 10 depicts the idea of Goodman plot for fatigue evaluation.



(a) experimental test equipments (b) PCB on the fixture



(c) measurement locations on the PCB

Figure 7. Experimental setup for random vibration tests

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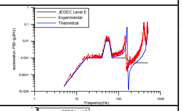
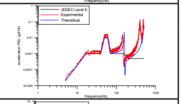
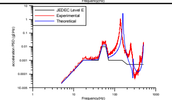
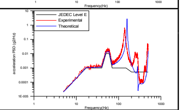
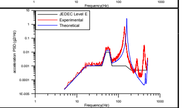
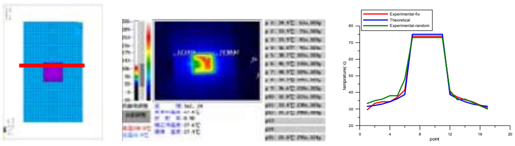
Table 2. Acceleration response for the PCB with thermal and random vibration loadings

Location		Acceleration PSD
Exp rms (g)	FEA rms (g)	
1		
2.561	1.332	
2		
2.545	1.315	
3		
3.250	3.719	
4		
2.814	3.708	
5		
2.641	3.664	



(a)FE model (b) experiments (c) temperature curve

Figure 8. Comparison of temperature between FEA and experiments

Table 3. Response distributions for the PCB with thermal (75℃) and random vibration loadings

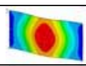
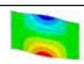
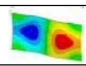
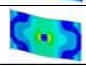
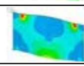
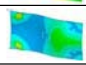
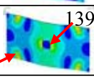
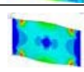
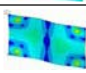
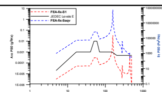
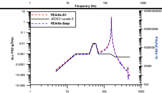
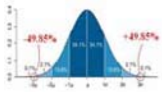
frequency / ODS	152.5(Hz)	280.49(Hz)	436.13(Hz)
Uz			
σ_1			
σ_{eqv}	1399 364 		

Table 4. Prediction of stress PSD, rms values and ranges for the PCB with thermal (75℃) and random vibration loadings

location	Stress PSD	Stress rms (KPa)	Stress range (KPa)
364		$\sigma_{1,rms} = 0.737$ $\sigma_{eqv,rms} = 34.5$	$\sigma_1 = \pm 2.211$ $\sigma_{eqv} = \pm 103.5$
1399		$\sigma_{1,rms} = 72.2$ $\sigma_{eqv,rms} = 63.6$	$\sigma_1 = \pm 216.6$ $\sigma_{eqv} = \pm 190.8$



Figrue 9. Illustration of normal distribution [12]

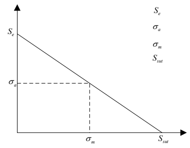


Figure 10. Illustration of Goodman line for fatigue evaluation

4. Conclusions

This work presents the finite element simulation and experimental verification of the PCB with thermal input and random excitation compound loadings. The heating pad is adhered on the top of the package as the heating source to provide with constant temperature. The FE model of PCB with the heating pad in thermal loading is constructed and solved for temperature distribution in steady state. The PCB FE model is then calibrated by comparing modal parameters obtained from FEA and EMA to validate the equivalent PCB analytical model. The verified FE model for the PCB with the consideration of thermal input is then solved for the spectrum response analysis and compared with experimental results, in terms of temperature distributions and acceleration PSDs. Finally, the stress fields in the PCB can be predicted and evaluated for possible fatigue failures. This work lays out the analytical approach for the PCB subject to thermal and random vibration inputs and verified by the experimental results. The developed methodology is beneficial to package industry for the evaluation of fatigue failures due to coupling effects of thermal and random vibration loadings.

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