International Journal of Aquatic Science
ISSN: 2008-8019
Vol 12, Issue 02, 2021

Prediction Of Fatigue Life Of Solder Joints Under Random Vibrations Using Numerical Simulation

SaravanaKumar K[1],SaravananSambasivam[2], Naveen S[3]

[1]Assistant Professor, Departtment of Production Engineering, PSG College of Technology, Coimbatore and 641004, India
[2]Professor, Department of Production Engineering, PSG College of Technology, Coimbatore and 641004, India
[3]PG student, ME Manufacturing Engineering,PSG College of Technology, Coimbatore and 641004, India

Email : [1]ksk.prod@psgtech.ac.in

Abstract: Electronic devices are increasingly used in severeengineering environments such as automotive, aerospace and defence. It can be subjected to many different forms of vibration over wide frequency ranges and acceleration levels. Apart from the extreme temperature and possibly high humidity, vibration can also be major cause of failure of these components. The test vehicles for the vibration tests consist of twelve Ball Grid Array (BGA) components with built-in daisy-chained circuits, which was assembled on centre of a printed circuit board (PCB). First three mode shapes and their corresponding natural frequencies were obtained from modal analysis using finite element analysis. Random vibration analysis was performed by giving Power Spectral Density (PSD) values as input to numerical simulation. Fatigue life of the BGA144 solder joints was predicted by Stenberg equation.

Keywords: Random vibration, Lead-free solders. finite element analysis, fatigue life

1. INTRODUCTION

Electronic devices reside almost all modern equipment and machinery and their reliability has always been a major issue for design and manufacturing engineers. The use of new materials, new manufacturing processes, new trends in consumer products, new performance requirements and applications are all great challenges for the engineers and researches in their pursuit for the best and most reliable design in electronics devices. The reliability of the solder joints is a key factor affecting the development of PBGA packaging technology. A survey compiled by the U.S. Air Force shows that approximately 55% of the failures of electronic devices are related to high temperatures and temperature cycling and 20% of the failures are due to shock and vibrations [1]. The vibration-induced failure of electronic devices is one of the most important reliability issues and has been widely studied by many researchers [2] The most challenging issue in the packaging industry is to estimate the fatigue life of the critical solder joints more rapidly and effectively during the design process [3]. The property and fatigue life of electronic components under vibration mainly depend on the solder joints [4].Gharaibeh[5] has analyzed the reliability of vibrating electronic assemblies the results of his research are suggests a very useful design for electronic products in vibration loading environments. Fang Liu et al. [6]have investigated numerical simulation and fatigue life estimation of BGA packages under random vibration loading. The life of the solder joint was recorded under random vibration using FEM (ABAQUS) and experiment (Miner's rule and random vibration theory). The comparison results that predicted fatigue life of BGA solder joints matches the experimental results with reasonable accuracy. The research concludes that solder joints at the four corners of BGA packages have higher peeling stress values than others, especially at the both sides of solder joints near PCB and BGA. Jiang xia et al. [8] have presented a comparison of the fatigue life prediction of solder joints under random vibration load by several popular frequency domain methods. And the authors proposed that Tovo – Benasciutti method is the best method for both life estimation of BGA package and PoP package.

Tonget al. [10] have compared the lifetime between the experimental results with the predicted results. And the authors suggest a methodology to predict the fatigue life of PBGA solder joints under vibration. Lionel et al. have investigated the mechanical fatigue life of SAC305 solder joints under sinusoidal and random vibration. Random vibration durability was estimated using experimental results along with data from sinusoidal vibration tests and finite element analysis. Kyeonggon Choi et al. [11] have estimated the reliability of various Pb-free solder joints under harsh vibration conditions. In this research combined vibration tests were performed on the various solders under severe environments, from experimental Sn Cu Al (Si) solder demonstrated the best reliability. The reliability of the solder joint was determined by measuring the electrical resistance using a multi-meter. Park et al. [12] have proposed MoS is the effective methodology to predict and ensure more reliable mechanical safety on the solder joints. Zhou et al. [13] have investigated the vibration lifetime of both Sn37Pb and Sn3.0Ag0.5Cu solder joints in PBGA components using a combination of finite element analysis (FEA) and sinusoid vibration tests. An assessment methodology for the vibration lifetime prediction of PBGA solder joints based on the SeN fatigue curve, FEA and an adjusted Steinberg model is developed, and the proposed prediction model of vibration lifetime is confirmed by random vibration tests. Yusuf Cinar et al [14] have investigated on failure mechanism of FBGA solder joints of memory modules due to harmonic excitation by using experimental and finite element method. It showed that failure occurs due to the motion of PCB and package and solder joints are highly impacted under vibration. Additionally, the most affected part under vibration is found to be soldered joint near the PCB.
The current challenge is to conduct the vibration lifetime analysis rapidly and accurately. Numerous experimental studies have been devoted to establishing an effective and valid methodology for the vibration lifetime prediction of solder joints. Leaded solder balls used in mounting of chips on the PCB’s are restricted by Restriction of Hazardous Substance (RoHS) directive as lead is one of the most toxic materials next to cadmium and mercury. Also, they cannot be disposed of safety without affecting the environment after its useful life. So, industries are moving towards usage oflead-free solders. In order to predict the lead-free solders life under vibration loading conditions is necessary to determine its material properties and its dynamic characteristics. Hence through this work the fatigue life of electronic package under random vibration loads can be determined. In this paper modal analysis of PCB package has been conducted. Their natural frequencies and corresponding mode shapes have been evaluated. Fatigue life of SAC305 has been predicted by using the FE analysis and Steinberg equation.

2. MATERIALS AND METHODS

The solder ball is manufactured based on common standard called Joint Electron Device Engineering Council (JEDEC).
The flowchart shown in Fig.1 describes the main steps involved in the prediction of vibration fatigue life of a lead-free solder joint in electronic packages. The first step is to identify the research gap and formulate the problem definition and study about the electronic packages and the components involved in ball grid array. Data collection is used to identify the various material properties like substrate, PCB, mechanical and geometrical dimensions of BGA to develop a finite element model. And the fatigue life of solder joint under random vibration loading condition is to be evaluated by using the random vibration analysis and Steinberg equation.

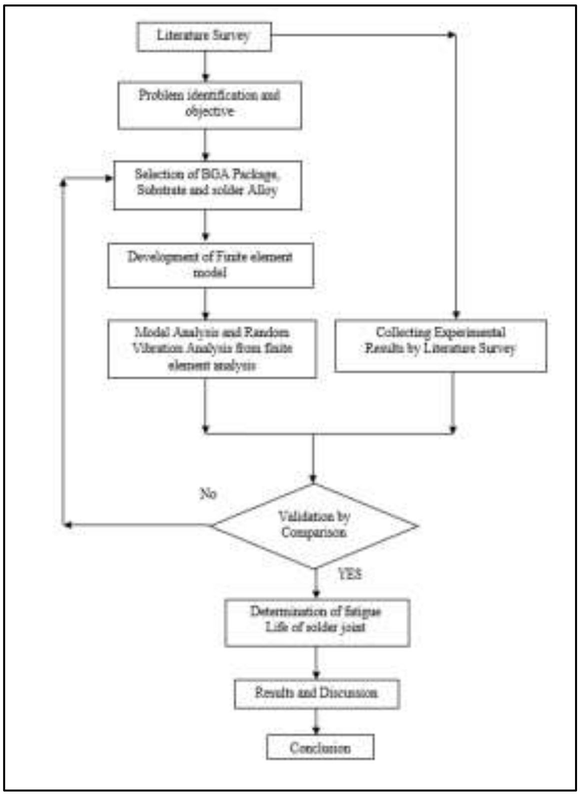


Fig.1 Methodology Flowchart Showing the Prediction of Solder Life

2.1 Molding Component (Die)

Silicon is selected as a molding component material from the literature survey and Joint Electron Device Engineering Council (JEDEC). The properties of the silicon material are shown in Table 1.

Die Material	Properties	Metric Values
Silicon	CTE [@25°C]	2.6 ppm/°C
	Young's modulus	110 GPa
	Poisson ratio	0.24

Table 1Molding Component (Die) Properties [17]

2.2. Printed Circuit Board

The PCB tested in this project is made up of FR-4 material. The FR-4 glass epoxy is a most common and versatile high-pressure thermoset plastic laminate grade with high strength to weight ratio. With near zero water absorption and it is most commonly used as an electrical insulator possessing considerable mechanical strength.The material has the ability retain its high mechanical values and electrical insulating qualities in both dry and humidity conditions. The properties of the substrate material are shown in Table 2.

2.3 Solder Material

The solder joint is made of lead-free material SAC305 is to be used because it has lower melting temperature compared with leaded solder alloys. The properties of solder alloy are shown in Table 3. The solder alloy is selected based on literature survey.

	Properties	Metric Values
FR4 Multi-functional Park Nalco N4000-6 FC	Glass transition temperature Tg – DSC Tg – TMA	 175^{o}C 170^{o}C
	X/Y CTE [-40^{o}C ~ 125^{o}C] Z Axis Expansion [50^{o}C ~ 260^{o}C] Z Axis CTE [50^{o}C to Tg] Z Axis CTE [Tg to 260^{o}C]	12 -15 ppm /^{o}C 4.1% 70 ppm/^{o}C 320 ppm/^{o}C
	Young’s Modulus	29.9 / 25.1 GPa
	Poisson Ratio (X / Y)	0.16 / 0.14
	Moisture Absorption	0.10 Wt. %

Table 2 Substrate Material Properties [17]

2.4 Bga 144 Specifications

A Fine ball grid array (FBGA) is a surface-mount packaging (a chip carrier) used for electronic circuits. These types of packages are used to mount devices such as microprocessors in a circuit board. BGA can able to provide more interconnection pins that can be put on a dual in-line or flat package.

One BGA package made of lead-free solders SAC305 is mounted on the PCB using surface mount technology and the solder balls connections are made through daisy chain for resistance monitoring and to find the crack or failure propagation in the whole package during the experimental testing. The size of the PCB used in this research is 132mm × 77mm as per the JEDEC standard [16]. The packages are dummy of typical packages used in applications such as Tablets, smart books, net tops andinternet monitors.

	Properties	Metric Values
	Temperature Solidus Liquidus	 217°C 220°C
SAC305 Sb96.5/Ag3.0/Cu0.5 (Pb-free)	Coefficient of thermal expansion	23.5ppm/°C
	Youngs Modulus	51GPa
	Tensile strength	50 MPa
	Density	7400 Kg/m^3

Table 3 Solder alloy properties [8]

3. FINITE ELEMENT ANALYSIS

The size of the Printed Circuit Board (PCB) is 132 x 77 x 0.8 mm as per JEDEC standard and it is made up of FR4 material. BGA with Solder balls is mounted on centre of the PCB with a fixed support.

3.1 Boundary Conditions

The PCB geometry modal is constrained in four corners as a fixed support as shown in Fig.2. One of the important assumptions made during the FE element modal analysis is that the materials are assumed to be linear isotropic in nature even though the PCB. This is an important assumption to perform the modal analysis because the system as a whole is considered as a linear system.

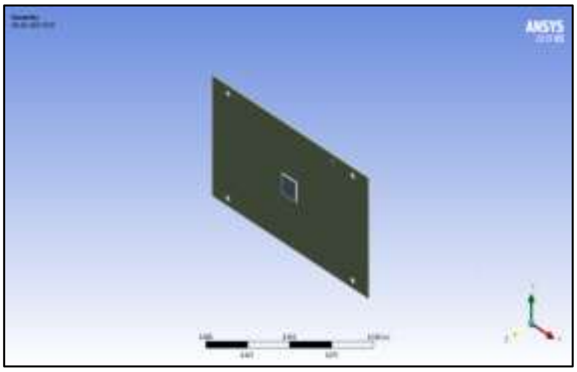


Fig.2 PCB Model with Fixed Support

The geometry modal is meshed with an element size of 1mm as shown in Fig.3 and the number of elements presented in the modal is 58567.

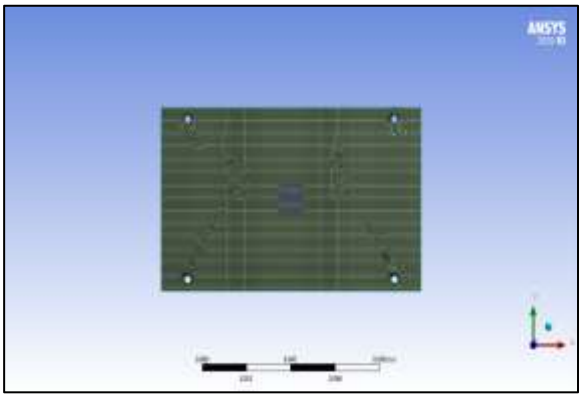


Fig.3 Mesh Modal with Element Size 1mm

3.2 Modal Analysis

Modal analysis is used to determine the dynamic characteristics of the PCB such as mode shapes and natural frequencies. Modal analysis was carried out using FEA and will be validated by literature review experimental modal analysis

From modal analysis first three mode shapes and natural frequencies were obtained from finite element analysis using Ansys workbench.

3.2.1 First Modal Analysis And Its Mode Shape

The first natural frequency of the package mounted on PCB is found to be 179.21 Hz and the corresponding mode shape has been shown in Fig.4

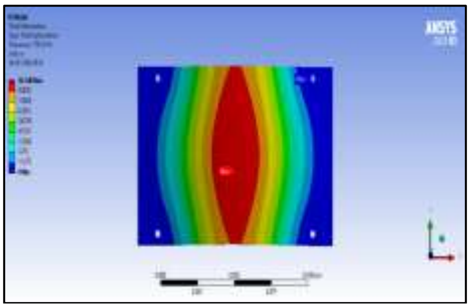
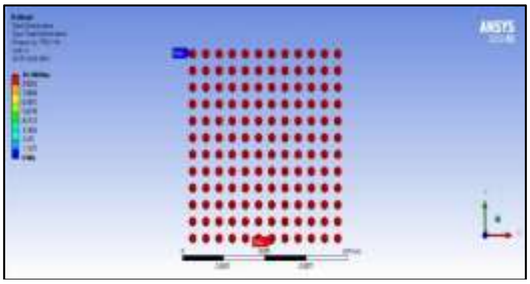


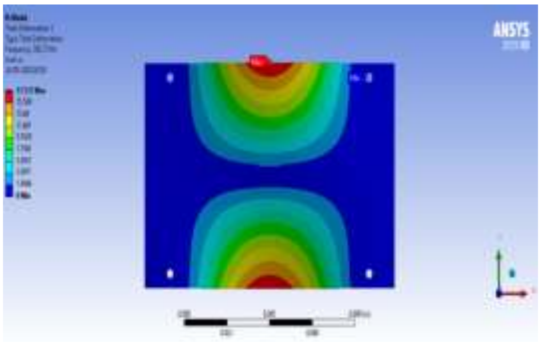
Fig.4(a) Stress Distribution on PCBand



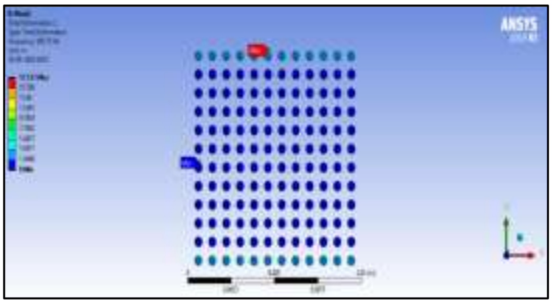
(b) Stress Distribution on Solder Ballfor First Natural Frequencyand its Mode Shape of FBGA 144 on PCB

3.2.2 Second Modal Analysis And Its Mode Shape

The second natural frequency of the package mounted on PCB is founded to be 303.73 Hz and the corresponding mode shape has been shown in Fig.5.



(a)

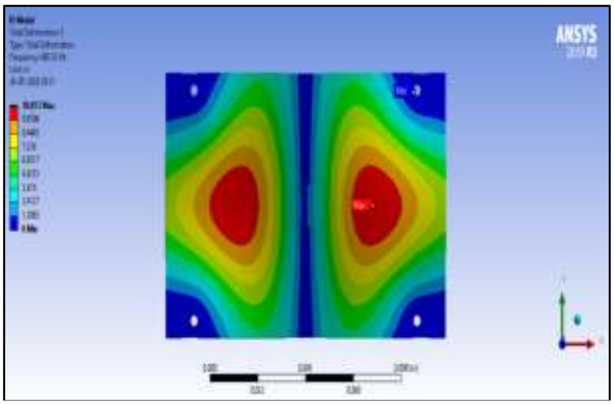


(b)

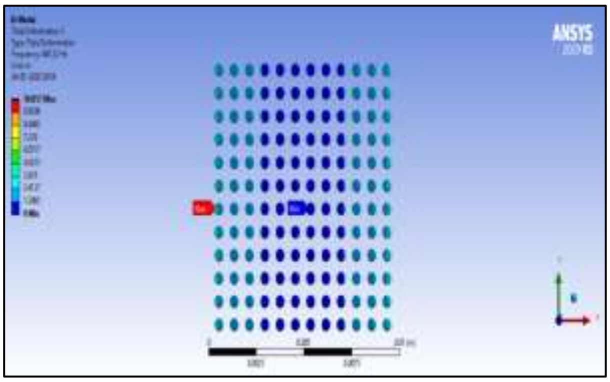
Fig.5(a) Stress Distribution on PCB and (b)Stress Distribution on Solder Balls for Second Natural Frequency and its Mode Shape of FBGA 144 on PCB

3.2.3 Third Modal Analysis And Its Mode Shape

The third natural frequency of the package mounted on PCB is founded to be 445.32 Hz and the corresponding mode shape with deformation of 10.857 m as shown in Fig.6.



(a)



(b)

Fig.6(a) Stress Distribution on PCB and (b) Stress Distribution on Solder Balls for Third Natural Frequencyand its Mode Shape ofFBGA 144 on PCB

3.3 Random Vibration Analysis

Random vibration analysis was carried out in Ansys workbench to find the dynamic characteristics of the PCB under vibration loading conditions. PSD values were given as inputs for analysis are shown in Table 4 and Fig.7.

4. RESULTS AND DISCUSSIONS

4.1 Model Analysis

The natural frequencies obtained from the FE analysis is shown in Table 5 and Fig.8. And the results were compared with the experimental results, which collected from literatures.

Table 4 Frequency Breakpoints of Power Spectral Density[16]

FREQUENCY (Hz)	PSD LEVEL(G^2/Hz)
5	0.0001
10	0.003
40	0.003
50	0.013
70	0.013
200	0.001
500	0.001

4.2 Random Vibration

The critical solder ball that subjects to maximum stress is found out by looking into equivalent stress results. The maximum equivalent stress of FBGA144 on PCB was found to be 8.655 MPa as shown in Fig. 9. The probability of failure of the PCB was found as 68.27% for a scale factor of 1 sigma.

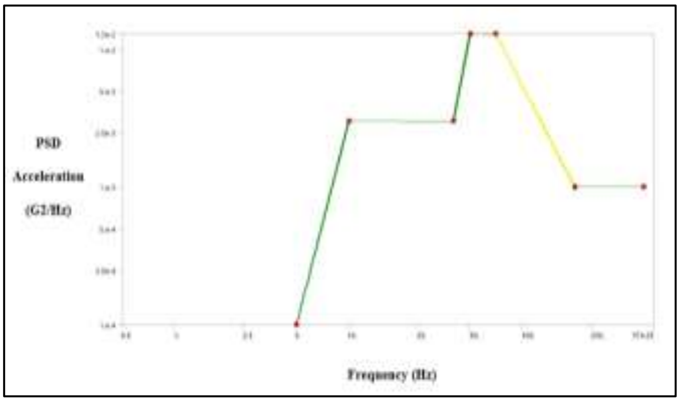


Fig.7 Frequency vs PSD Acceleration Graph

Table 5 Finite Element Analysis Results of the PCB with Package

Analysis Results Obtained Using FEA (Natural Frequency (Hz))		
Mode 1	Mode 2	Mode 3
179.21	303.79	445.32

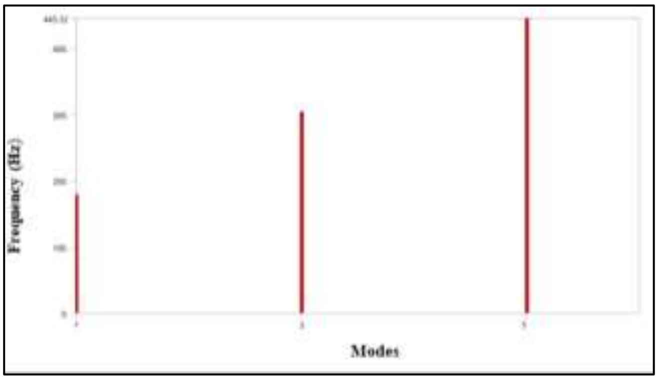
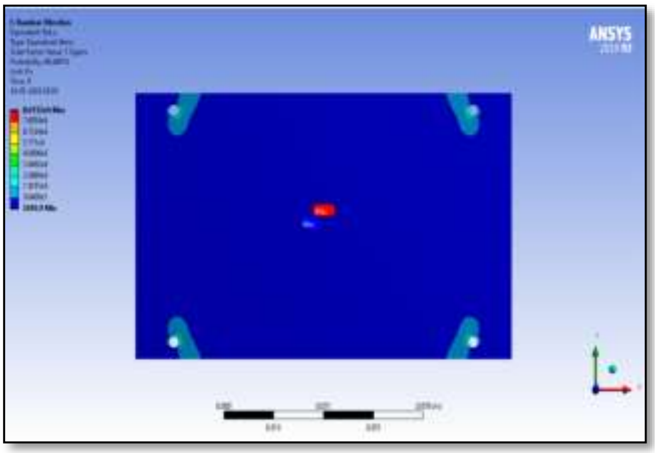
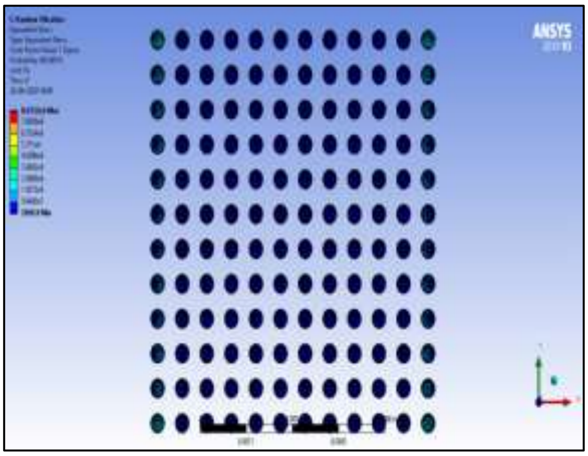


Fig. 8 Mode vs Frequency Graph



(a)



(b)

Fig.9(a) and (b) Equivalent Stress of PCB with FBGA144

4.3 Calculation Of Fatigue Life

The fatigue life of the FBGA144 is calculated using the procedure as described by Steinberg. The desired natural frequency of PCB assembly that will provide a fatigue life of 20 million stress reversals for the most critical elements [1] will be estimated using Equation (1).The Desired Natural Frequency,

$$f_n = \left(\frac{29.4tc\sqrt{\frac{\pi}{2}}pl}{0.000222B} \right)^{0.8} \qquad (1)$$

Where,

B = length of PCB edge parallel to component located at the centre of the board, (in) = 3.078 inch.

l = length of component, (in) = 0.4724 inch

t = thickness of PCB assembly, (in) = 0.0314 inch

c = 2.25 for lead-free chip carriers. (Constant value)

p = Input PSD level at resonant frequency (G^2/Hz) = 0.001 G^2/Hz

The desired natural frequency of PCB withFBGA144 is calculated from equation (2)

The Desired Natural Frequency, $f_n = \left(\frac{29.4x0.0314x2.25\sqrt{\frac{\pi}{2}}x0.001x0.4724}{0.000222x3.078} \right)^{0.8}$ (2)

$$f_n = 34.46\ Hz.$$

The fatigue life for the PCB with package can be determined from equation (3)

$$L_f = \frac{20x10^6}{f_n x3600} (3)$$

Here, Number of stress reversals is 20x10^6 Pa [1]. Fatigue life of the component in hours is calculated using equation (3) and the value of fatigue life obtained was 161 hours.

L_f=161 hours

Fatigue Life

The fatigue life of the SAC305 solder joint was predicted asper the Steinberg equation [1] by evaluating the natural frequencies (Modal analysis) and Random Analysis. The comparison of the experimental results which collected from literature survey is shown in Table 6. Finally, the fatigue life was found to be 161 hours.

5. CONCLUSION

The modal analysis of the printed circuit board with package is obtained by fixing the degrees of freedom with four screws and the first three mode shapes and natural frequencies extracted from finite element analysis. The first three natural frequencies are 179.21Hz, 303.73Hz and445.32Hz respectively. The random vibration analysis evaluated by giving PSD values as input and the probabilityof failure of the PCB was found as 68%. Fatigue life calculation is carried out analytically, by using the power spectrum density (PSD) response value, obtained fromrandom vibration analysis. The fatigue life of PCB with FBGA144 found to be 161 hours from FEM analysis using Steinberg equation.

Table 6 Comparison of fatigue life of various solder joints under random vibrations

Authors	Solder Alloy	BGA	PCB size	Frequency (Hz)	PSD	Fatigue Life (min)		Natural Frequencies	
						Predicted (min)	Experiment (min)	FEA (Hz)	Experiment (Hz)
Tong An et al. [15]	Sn37Pb	PBGA 256 Pitch 2	300×180x2 .3 FR4	15-2000	7G 11G 18G	639.23 248.22 25.6	NA NA NA	93.42 185.14 232.09	92.67 186.98 233.98
Da Yu et. al.[9]	SAC305 SAC405	PBGA 144 Pitch 0.5	100x50x0.6 FR4	100-1000	0.15 0.25 0.15 0.25	698 121 308 93	395 113 282 102	281 519 768	282 521 757
Yusuf cinar et al. [14]	SAC305	NA	133.35x 30.00 x 1.295 FR4	20-2000	NA	NA	NA	940.31 1390.4 2080.8	954 1350 1990
Sakri et al. [7]	NA	Electronic device	240x 200x 1.5 FR4	100-1000	0.013	NA	96.48 hr	NA	48.56 92.37 105.90 210.17 220.03

Acknowledgments

The authors are thankful to PSG Management and Department of Production Engineering for providing the motivation and support to utilize the facilities in PSG College of Technology, Coimbatore-04.

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