International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

IJSRA

(Research Article)

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Effect of lead-free solder thermal interface material thickness on the reliability of electronic components in a random vibration environment

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International Journal of Science and Research Archive, 2024, 11(02), 898–908

Publication history: Received on 19 February 2024; revised on 28 March 2024; accepted on 30 March 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.11.2.0515

Abstract

The reliability of electronic components has persistently posed challenges for engineers. This study addresses the critical need of understanding the impact of random vibration on the reliability of lead-free solder as thermal interface materials (TIM) within electronic components. ANSYS software was deployed to design, develop, and simulate the electronic model, with a focus on the TIM. SAC405 lead-free solder served as the TIM, its thickness was varied between 0.01 to 0.06 mm (at 0.01 mm intervals). The results from this investigation reveal relevant correlations. As the TIM thickness increases, there's a noticeable reduction in stress and strain while the deformation increases. Remarkably, a direct relationship emerges between TIM thickness and fatigue life; thicker TIM correlates with increased fatigue life. In addition, at a TIM thickness of 0.01 mm, the fatigue life measurements were 2.76 x 104, 1.63 x 104, and 0.792 x 104 for Equations 1, 2, and 3, respectively. These findings carry profound implications for engineers, serving as a guiding framework to aid in the selection of optimal TIM thickness for electronic components if lead-free solders are used as TIM. Understanding these trade-offs between stress, strain, deformation, and fatigue life is pivotal, empowering engineers to make informed decisions during electronic system design and development, ultimately enhancing overall reliability. Using lead-free solders as TIM in electronic applications is proposed by this study due to the thermal and reliability benefits presented.

Keywords: Random vibration; SAC405; Reliability; ANSYS; Fatigue life; TIM

1. Introduction

The reliability challenges of electronic components are becoming more crucial because of miniaturisation [1]. The smaller the component, the more challenging it is to keep it working within specified environmental conditions. Environmental conditions could range from thermal environment, high and low temperature environment, vibration environment, etc. Vibration environment is crucial to electronic component reliability because it can lead to damage of the components before usage or during usage. Solder joints [2 – 5] are major components in electronic devices and it's important to investigate its reliability as it affects the electronic device operations. Lead-free solder joint subjected to vibration have been widely investigated by experimentation and simulation (Finite Element Analysis) [6 - 11].

Muhammad et al. [12], investigated the remaining useful life (RUL) of electronic modules, considering rugged random vibration and operational conditions, analysing the effects on solder joints of a printed circuit board (PCB). Their modal analysis identifies the natural frequencies, mode shapes, and factor ratios of the PCB and components, which was confirmed by experimental sine sweep results. The authors used random vibration testing between 10 Hz to 2000 Hz, and it records printed circuit board (PCB) failure times, while ANSYS software assesses the acceleration response and stress power spectral density (PSD) of the critical solder joints.

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Che and Pang [13], developed a methodology for assessing flip chip solder joint fatigue life via vibration fatigue testing and analysis. It involves tests with constant and varying G-level input excitation. While utilising Miner's rule, it shows non-conservative predictions, prompting the use of finite element analysis (FEA) with a global-local-beam modelling approach to calculate natural frequencies, compared to experimental data. The authors used quasi-static FEA method to explore the solder joint stress-strain behaviour, while harmonic FEA was used to predict the fatigue life. In another study by Lall and Thomas [14], the authors examined the health monitoring of electronic assemblies enduring 14 G vibration failure at 55°C. Strain gauges were attached on a PCB to capture data for analysis, which includes time-frequency analysis (TFA), joint time-frequency analysis (JTFA), principal component analysis (PCA), and independent component analysis (ICA). The authors noted that high-frequency components increase in occurrence and amplitude with vibration time. In addition, PCA and ICA effectively captured strain behaviour pre- and post-failure, aiding the prognostics. The authors inferred that the variance in the trends in the principal components of instantaneous frequency serve as a health monitoring feature during vibration, indicating behaviour changes until failure.

This research is unique because it is different from what is available in the literature. In literature, a lot of works have been done on the reliability of lead-free solder joints with or without vibration, but not on lead-free solder as a thermal interface material. Hence, this research delves into the effect of lead-free solder thermal interface material thickness on the reliability of electronic components in a random vibration environment.

2. Material and methods

The fundamental materials employed in this research comprise a silicon chip, SAC405 Thermal Interface Material (TIM), and an aluminium heat sink. These materials were strategically selected to create a representative microelectronic model for the ensuing analyses and simulations. Table 1 encapsulates the critical material properties associated with the silicon chip, SAC405 TIM, and aluminium heat sink. These properties encompass a comprehensive overview of the characteristics essential for understanding the behaviour of materials within the microelectronic system. Given the primary emphasis on vibration analysis in this study, particular attention was directed towards three pivotal material properties for the simulation:

- Young's Modulus, E (GPa): This property quantifies the material's stiffness and is crucial for assessing its response to mechanical stress.
- Poisson's Ratio (μ): Poisson's ratio is imperative for understanding the material's deformation behaviour under stress and plays a pivotal role in vibration analysis.
- Density, ρ (kg/m^3): Density is a fundamental parameter influencing the mass distribution within the microelectronic system, thereby influencing its vibrational characteristics.

These selected properties were deemed most pertinent to the vibration analysis, aligning with the main objective of this research. By focusing on these specific material attributes, the study aims to gain an understanding of the microelectronic system's response to vibrational forces. The subsequent sections delve into the implications of these material properties on the vibrational dynamics of the simulated system.

Table 1 Material Properties [1, 15]

Component Materials	**Young's Modulus, E (GPA)**	**Poisson's Ratio, μ**	**Density, ρ (kg/m^3)**
Silicon Chip	130	0.22	2330
SAC405 TIM	49	0.38	7440
Aluminium Heat Sink Base	71	0.33	2770

The microelectronic model under investigation was meticulously designed to capture the essential features of the system. The design process involved specifying the geometric configurations, material properties, and the structure of the silicon chip, SAC405 TIM (Thermal Interface Material), and the aluminium heat sink base. The aim was to create a representative model that accurately reflects the physical characteristics of the real-world components. The designed microelectronic model was subjected to comprehensive simulation using ANSYS Workbench software. ANSYS Workbench, a widely recognized engineering simulation platform, was chosen for its versatility and capability to perform detailed analyses. The simulation aimed to predict and analyse the behaviour of the microelectronic components under various operating conditions. The outcomes of the simulation were visually presented in Figure 1.

This figure serves as a comprehensive illustration of the developed microelectronic model, highlighting its structural components and their interrelationships. The visual representation in Figure 1 aids in conveying a clear understanding of the simulated system. To ensure precision in the simulation, Table 2 provides detailed dimensions for key components, namely, the silicon chip, SAC405 TIM, and aluminium heat sink base. These dimensions were crucial for accurately modelling the physical attributes of the components in the simulation. The values presented in Table 2 serve as a reference for the size and proportions of the components used in the microelectronic model. By combining meticulous design, simulation using ANSYS Workbench, the visual representation in Figure 1, and detailed dimensions in Table 2, this method facilitated a thorough investigation into the behaviour and performance of the microelectronic system. The integration of these elements contributes to the reliability and relevance of the findings presented in this study.

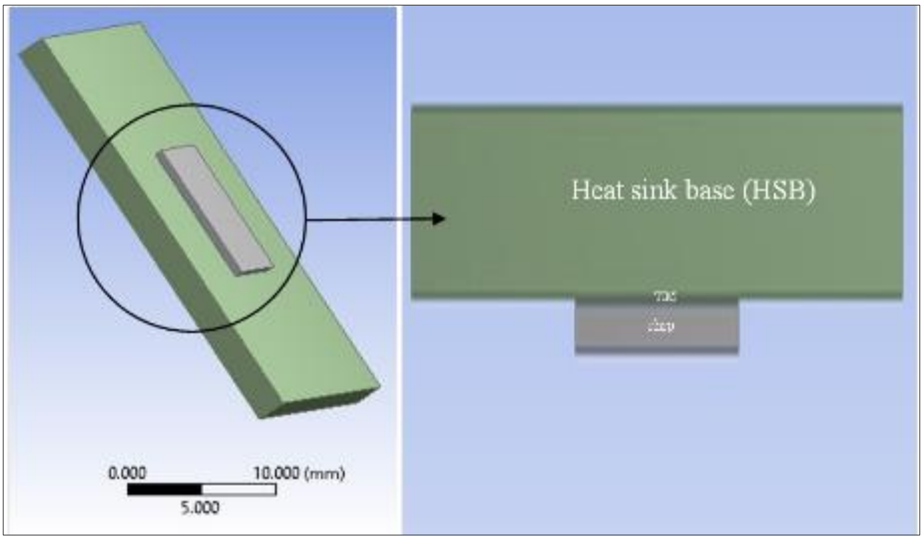

Figure 1 Designed model

Table 2 Dimensions of components

Component	Length (mm)	Breadth (mm)	Thickness (mm)
Chip	10	10	1.0
TIM	10	10	0.01 – 0.06
Heat Sink Base	20	20	2.0

2.1. Modal Analysis

In this study, the research primarily relies on modal analysis as its fundamental method. Modal analysis is a contemporary approach utilized to examine how structural systems behave in terms of dynamics within the frequency domain. A 'mode' signifies the inherent vibration pattern of a mechanical structure. Each mode possesses distinctive attributes like modal shape, natural frequency, and damping ratio. Vibration modes essentially encapsulate the comprehensive nature of an elastic system's characteristics. This study employs this method to delve into the structural modal properties of lead-free solder TIM (Thermal Interface Material) within an electronic component at a specified frequency. The aim is to predict how the system responds to both internal and external disturbances. Once the model was constructed, analysis types and options were chosen in alignment with the research objectives. Specific supports, boundary conditions, and constraints were defined and implemented. Simulation post processing outputs were acknowledged, and the model configuration was resolved. The obtained results included frequency data and deformation, which were examined concerning Power Spectral Density (PSD) displacement input analysis.

2.2. Random Vibration Fatigue Life Model

The fatigue life of the TIM was analysed using the Basquin's law for elastic strain amplitude as presented in Eq. 1 [16], Basquin's law for stress amplitude as presented in Eq. 2 [6], the Coffin-Mason empirical equation with elastic strain presented in Eq. 3[16]. In addition, other researchers have applied Basquin's power law and Miner's rule [12].

$$\frac{\Delta\epsilon_e}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b \qquad \text{............(1)}$$

where $\Delta\varepsilon_e$ is the elastic strain amplitude, $2Nf$ is the number of reversals to failure, σ'_f the fatigue strength coefficient, E the elastic modulus, and b the fatigue strength exponent given as -0.12 in [16].

$$\sigma_a = \sigma'_f\left(2N_f\right)^b \qquad \text{..................(2)}$$

Where σ_a is the stress amplitude. The values of 270.45 MPa for σ'_f and -0.2144 for b were adapted from [6].

$$\varepsilon = \frac{\Delta\varepsilon_t}{2} = 3.5\frac{\sigma_u}{2E}N_f^b \qquad \text{.............(3)}$$

Where ε is the strain amplitude, $\Delta\varepsilon_t$ is the total strain range, and σ_u is the tensile strength of the material got from Kumar et al., [17].

3. Results and discussion

In order to address the established 3D electronic model, it underwent a meshing process guided by the findings of the mesh dependency study conducted by [18]. The resulting meshed electronic model is visually depicted in Figure 2. The mesh itself comprises 82,204 nodes and 15,445 elements. The decision to employ a coarse mesh was influenced by the limitations of the simulation machine and the available memory resources. This approach was chosen to ensure compatibility with the computational capabilities at hand.

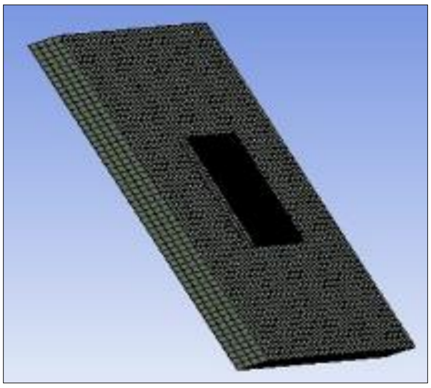

Figure 2 Mesh with 82,204 nodes and 15,445 elements

3.1. Effect of Random Vibration on TIM Modal Response

Figure 3 provides a visual representation describing the relationship between frequency and mode across various Thermal Interface Material (TIM) thicknesses. This correlation between mode and frequency assumes vital significance in vibration analysis, offering crucial insights into the behaviour of the electronic component under investigation. The plotted data illustrates a noticeable trend wherein an increase in the mode number corresponds to an increase in frequency. Remarkably, the graphical representation distinctly portrays that the frequency peaks at mode 6, closely followed by mode 5. This observation underscores the criticality of modes 5 and 6 concerning the electronic component under examination. Interestingly, this aligns with the findings of Depiver et al. [16], who similarly observed the highest frequency occurrence for mode 6, thus corroborating the significance of these particular modes in the context of this study.

Furthermore, the study conducted by Yu et al. [6] shows a similar trend, noting that an increase in mode number corresponds to an increase in frequency. This convergence of findings from different studies reinforces the observed relationship between mode and frequency, giving weight to the claim that modes 5 and 6 hold substantial importance in the vibrational characteristics of the electronic component. Overall, the insights gathered from Figure 3 and the consistency in findings across studies highlight the pivotal role played by mode-frequency correlation in understanding the vibrational dynamics of the electronic system, particularly emphasizing the criticality of modes 5 and 6 within this context.

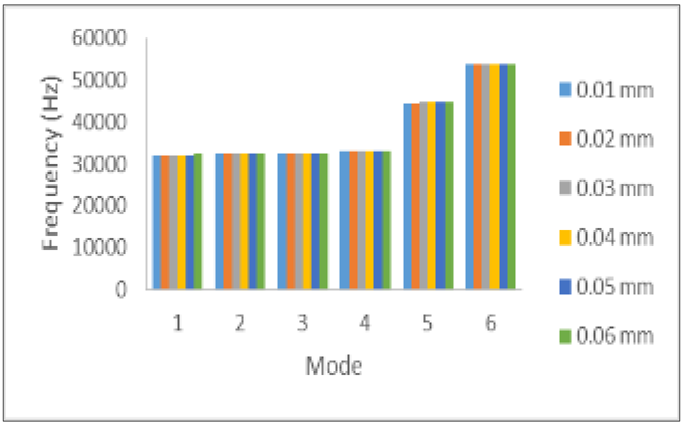

Figure 3 Plot of frequency to mode at different TIM thickness

The visual representation of the modal analysis deformation is depicted in Figure 4. The highest levels of deformation are evident in modes 2 and 3, indicating a correlation between the frequency levels in these modes and the resultant deformation. This suggests the importance of avoiding these particular frequency ranges to mitigate deformation issues. Depiver et al. [16] similarly identified mode 3 as exhibiting the highest deformation, aligning with the observations in this study.

A notable observation stems from the nearly identical frequencies observed in modes 2 and 3, indicating a similarity in the vibration characteristics at these frequencies. Figure 4 further illustrates a consistent pattern of deformation across TIM thicknesses for modes 1, 4, 5, and 6, maintaining a relatively similar level within each respective mode. However, an intriguing trend emerges for modes 2 and 3 concerning TIM thickness. It's evident that with an increase in TIM thickness, the deformation follows a corresponding increase, except for a decline observed at a thickness of 0.05 mm before resuming an upward trend at 0.06 mm. This fluctuation in deformation at these specific thicknesses highlights a critical point where the thickness appears to impact the deformation behaviour, deviating from the broader pattern observed across other modes.

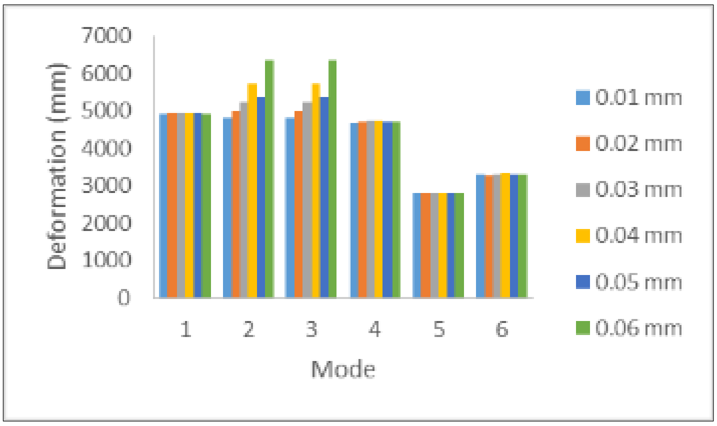

Figure 4 Plot of deformation against mode at different TIM thickness

Figures 3 and 4 serve as the primary sources of data used to derive the PSD (Power Spectral Density) displacement crucial for the vibration analysis. This analysis was conducted to measure the movement and behaviour of the electronic component under consideration. In Figure 5, the relationship between the displacement and the thickness of TIM across various operational modes was depicted. Among these modes, modes 2 and 3 exhibited increased displacement values, signifying their dominant behaviour within the electronic component. Interestingly, despite their prominence at a specific thickness of 0.01 mm, mode 1 displayed the highest displacement, deviating from the trend observed in other modes.

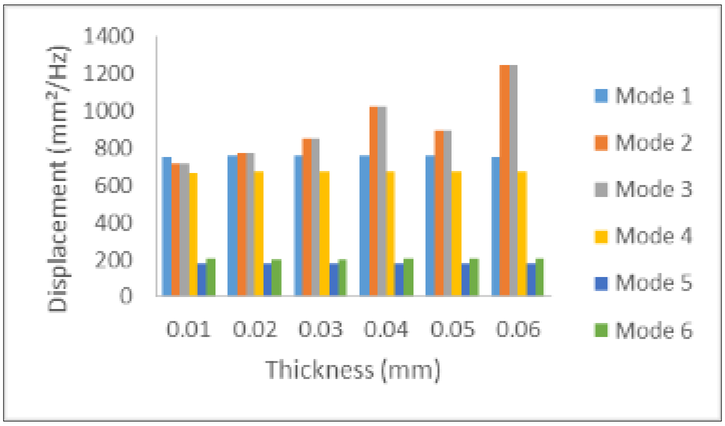

Figure 5 Plot of PSD displacement with TIM thickness at different modes

Figure 6 shows the total deformation after the modal analysis. From the contour plots in Figure 6, it is seen that the deformation is more around the edges of the SAC405 TIM. This observation is in agreement with different studies in the literature [6, 16]. In addition, it was observed that as the frequency increased, the deformation became more evident as seen in Figure 6. In addition, the deformations at modes 2 and 3 are critical because of their high deformation values.

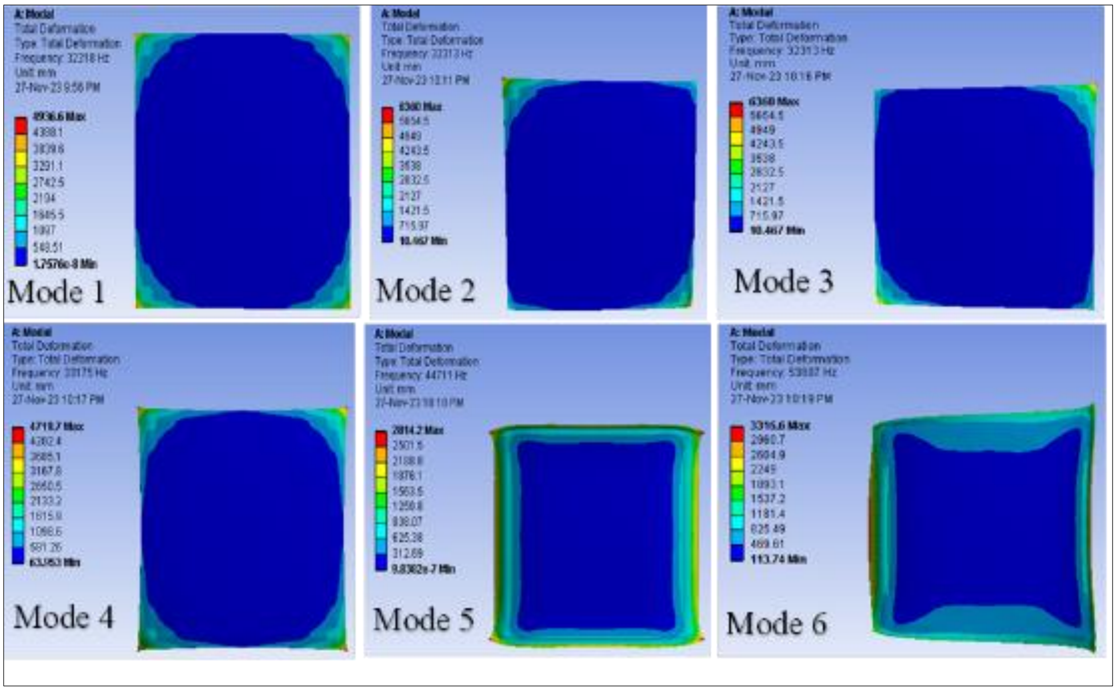

Figure 6 The total deformation of the six modes

3.2. Effect of Random Vibration on TIM Deformation Response

It is evident that vibration effects on the components deformation as seen in Figure 7. The deformations at 1, 2, and 3 Sigma corresponding to 68.27%, 95.45%, and 99.73% probabilities, respectively, are analysed. The contour plots in Figure 7 showed that the highest deformation occurred around the edges of the TIM SAC405. Meaning that the material is greatly stressed at the edges. Further analyses of Figure 7 showed that the deformation increases as the sigma number increased. Meaning that the higher the probability, the higher the deformation. A similar trend was observed for the different thicknesses studied, hence the presentation of the deformation contour plots for only 0.06 mm TIM thickness.

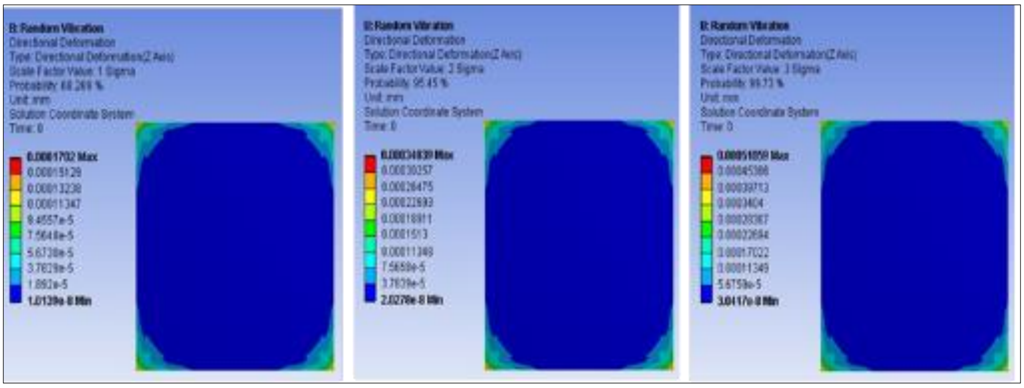

Figure 7 Deformation of TIM at 0.06 mm thickness for 1, 2, and 3 Sigma

3.3. Effect of Random Vibration on TIM Von Mises Stress and Deformation

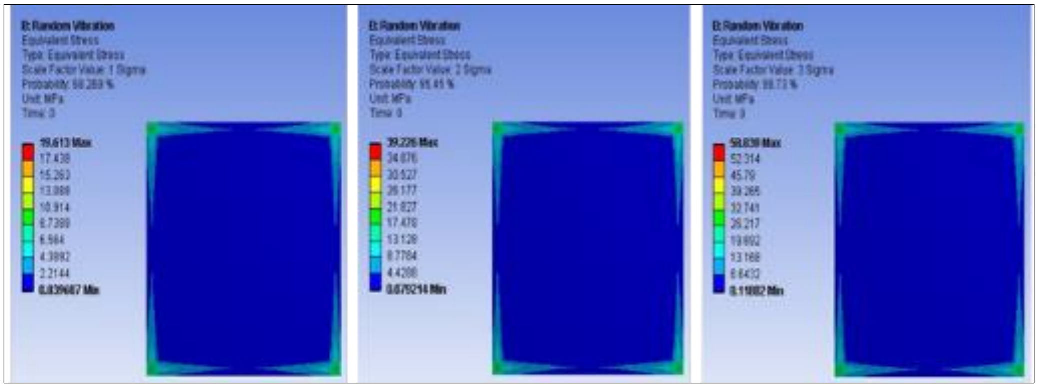

Figure 8 Pictorial view of von Mises stress at 0.06 mm thickness for 1, 2, and 3 Sigma

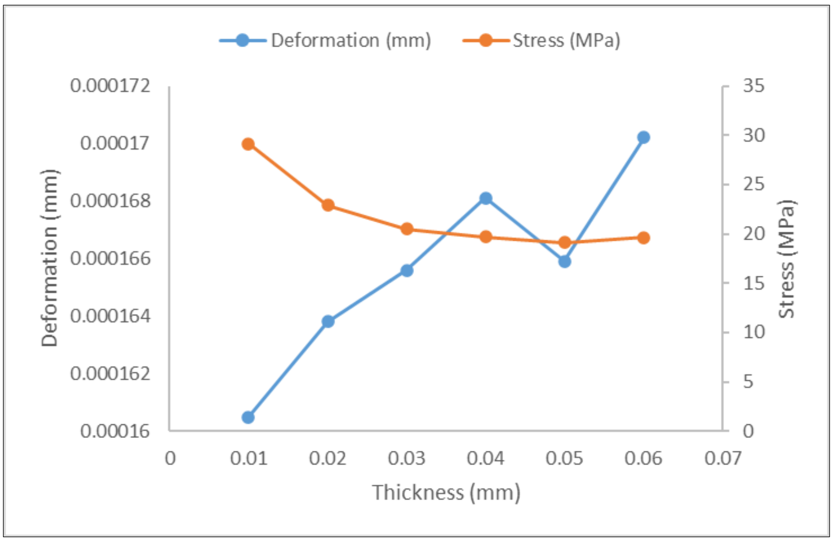

Figure 9 Plot of deformation with thickness with stress on the secondary axis

The pictorial views of the TIM von Mises stress for 1, 2, and 3 Sigma are presented in Figure 8. The stress contour plots show the distribution of stress on the SAC405 solder TIM. The highest stresses occurred around the edges of the solder TIM, showing the stress concentration. This finding agrees with other studies on solder joints carried out by [16]. The stress increased with an increase in the Sigma number. Figure 9 presents the deformation on TIM thickness with stress on the secondary axis. The deformation in Figure 9 shows that as the TIM thickness is increased, the deformation increases as well. However, at a thickness of 0.05 mm, the deformation dropped and increased at 0.06 mm thickness. It can be inferred that the thickness of TIM should be less than 0.05 mm, since the gap to fill between the chip and the heat sink is invariably small. However, the stress in Figure 9 showed that despite the increase in deformation, the stress reduced as the TIM thickness increases.

3.4. Effect of Random Vibration on TIM Elastic Strain and Deformation

The elastic strain of the TIM after vibration simulation is presented in Figure 10. The contour distribution plot in Figure 10 shows that the highest elastic strain occurred at the edges of the TIM solder. Analysis of the elastic strain in relation to the Sigma numbers showed that the elastic strain increases as the Sigma number increases. This trend is similar to the different thicknesses studied. Figure 11 presents the deformation on the TIM thickness with the elastic strain in the secondary axis. As the deformation increases with an increase in the TIM thickness, the elastic strain reduces. This signifies that the vibration effect is reduced as the thickness increases.

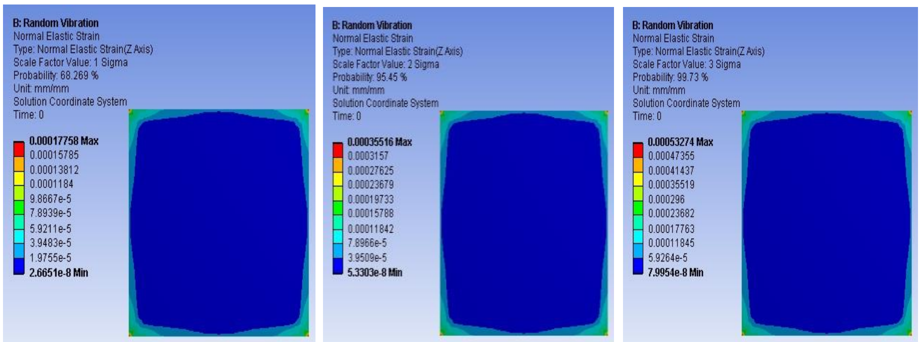

Figure 10 Elastic strain of TIM at 0.06 mm thickness

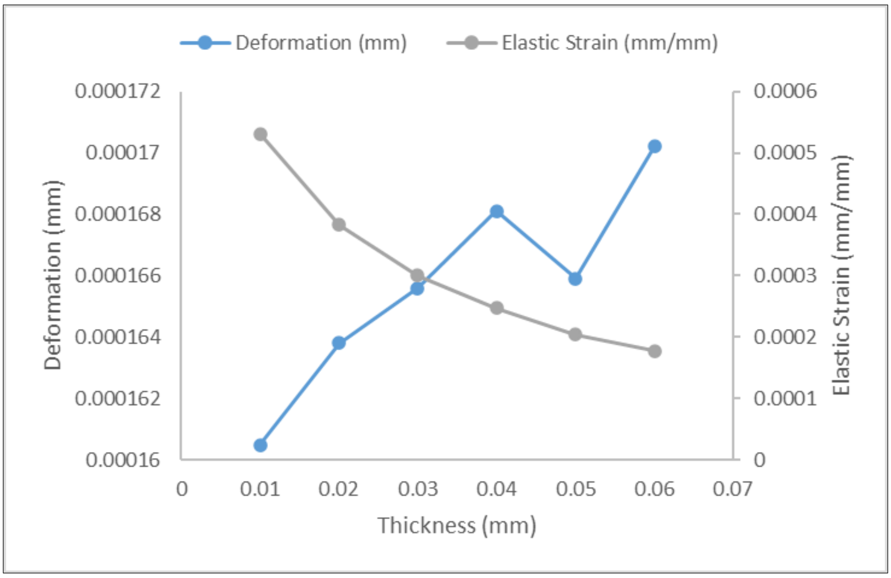

Figure 11 Plot of deformation on TIM thickness with elastic strain on the secondary axis

3.5. Relationship between Stress and Elastic Strain

The stress versus elastic-strain relation is studied and presented in Figures 12 and 13. Figure 12 shows that the stress and strain reduces as the TIM solder thickness increases. Therefore, the vibration effect on the stress and strain is reduced as the TIM thickness increases. The stress versus elastic strain plot in Figure 13 demonstrates that as the stress on the TIM solder increases, the elastic strain increases as well. The line of best fit to Figure 13 gave the linear relationship between stress and strain as $y = 27910x + 13.264$. Where y and x are stress and strain, respectively.

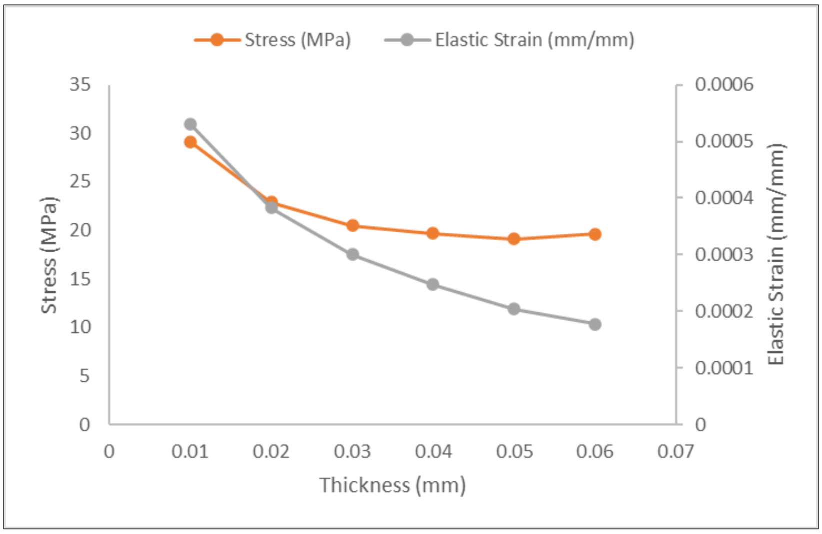

Figure 12 Plot of stress and elastic strain with TIM thickness

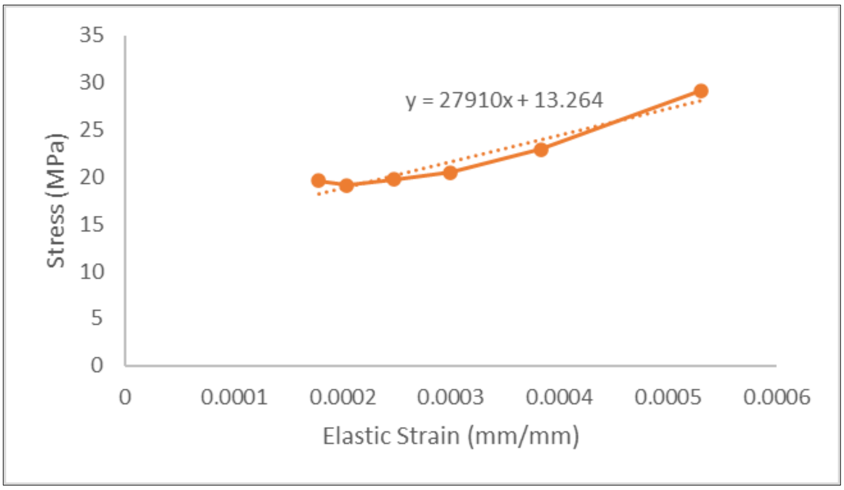

Figure 13 Plot of stress versus elastic strain

3.6. Effect of Random Vibration on TIM Fatigue life

The analysis in Figure 14 focused on evaluating the fatigue life of SAC405 TIM (Thermal Interface Material) solder across different equations representing Basquin's law for elastic strain amplitude, Basquin's law for stress amplitude, and the Coffin-Mason empirical equation for elastic strain (Equations 1, 2, and 3 respectively). At a TIM thickness of 0.01 mm, the fatigue life was determined as 2.76 x 10^4, 1.63 x 10^4, and 0.792 x 10^4 using Equations 1, 2, and 3, respectively. Interestingly, Equation 1 exhibited the highest fatigue life, followed by Equations 2 and 3. However, with an increase in TIM solder thickness, Equation 3 showcased the highest fatigue life, followed by Equations 1 and 2 in that order. This contrast indicates a shift in the relationship between thickness and fatigue life across the equations.

A noteworthy trend emerged across all equations: as the TIM solder thickness increased, the fatigue life consistently showed an upward trend, as illustrated by Equations 1, 2, and 3 in Figure 14. This general pattern implies that a thicker TIM solder tends to contribute to increased fatigue life, irrespective of the specific equation applied, although with varying magnitudes based on the equation utilised.

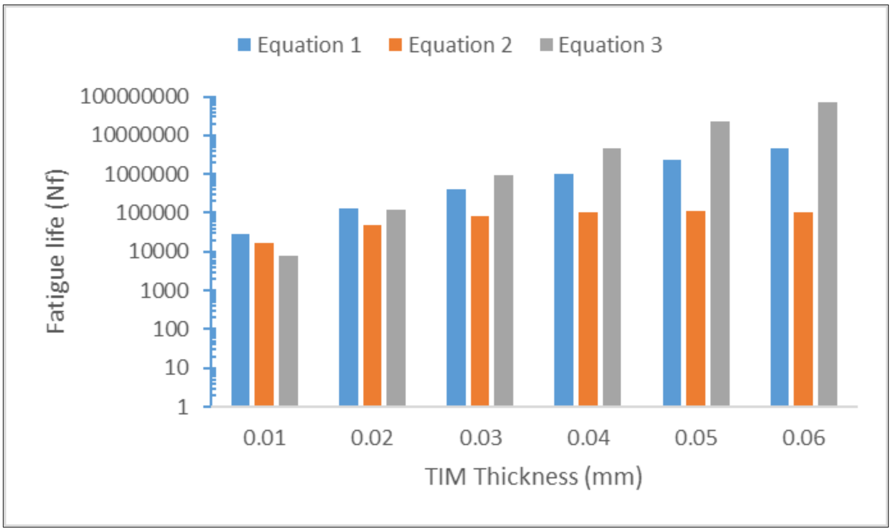

Figure 14 Fatigue Life of SAC405 TIM Subjected to Random Vibration

4. Conclusion

This work delves into the impact of random vibration analysis on SAC405 lead-free solder TIM in electronic components. The findings distinctly showcase the pronounced influence of random vibration on TIM performance within electronic setups. The TIM thickness emerges as a crucial factor influencing electronic component reliability. The research underlines a direct correlation between TIM thickness and fatigue life, indicating a positive relationship wherein increasing thickness increases fatigue life. However, it's crucial to exercise caution: maintaining a TIM thickness below 0.05 mm is advisable to mitigate heat retention issues within electronic components, despite the observed positive effects on fatigue life with increased thickness. This study therefore, proposes the use of lead-free solders as TIM in electronic applications because of its numerous thermal and reliability potentials.

Compliance with ethical standards

Acknowledgement

The authors would like to thank the Department of Mechanical Engineering, Delta State University Abraka, Nigeria, for providing the enabling environment for this research.

Disclosure of conflict of interest

The authors declare that there is no conflict of interest. No author received any grant for this research. This research is not funded by any grant.

References

[1] Ekpu, M. (2021). Investigating the Reliability of SnAgCu Solder Alloys at Elevated Temperatures in Microelectronic Applications. Journal of Electronic Materials 50, 4433-4441.

[2] Baishya, K., Harvey, D.M., Manzanera, T.P., Zhang, G., and Braden, D.R. (2023). Failure patterns of solder joints identified through lifetime vibration tests. Nondestructive Testing and Evaluation, 38(1), 147-171.

[3] Kavitha, M., Mahmoud, Z.H., Kishore, K.H., Petrov, A.M., Lekomtsev, A., Iliushin, P., Zekiy, A.O., and Salmani, M. (2021). Application of Steinberg Model for Vibration Lifetime Evaluation of Sn-Ag-Cu-Based Solder Joints in Power Semiconductors. IEEE Transactions on Components, Packaging and Manufacturing Technology, 11(3), 444-450.

[4] Kim, J., and Yoon, D. (2023). Thermomechanical Reliabilities of Pb-Free Solder Joints According to Ag Content in Harsh Environment. IEEE Transactions on Reliability.

[5] Wei, X., Alahmer, A., Ali, H., Tahat, S., and Vyas, P. P. (2023). Effect of temperature on the low cycle fatigue properties of BGA solder joints. Microelectronics Reliability, 146, 115031.

[6] Yu, D., Al-Yafawi, A., Park, S. and Chung, S. (2010). Finite element-based fatigue life prediction for electronic components under random vibration loading, 2010, Proceedings 60th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2010, 188-193, doi: 10.1109/ECTC.2010.5490900.

[7] Yu, D., Al-Yafawi, A., Nguyen, T.T., Park, S., Chung, S. (2011). High-cycle fatigue life prediction for Pb-free BGA under random vibration loading. Microelectronics Reliability, 51(3), 649-656.

[8] Jayesh, S., and Elias, P. (2019). Finite element modeling and random vibration analysis of BGA electronic package soldered using lead-free solder alloy – Sn-1Cu-1Ni-1Ag. Int. J. Simul. Multidisci. Des. Optim, 10, 1-11.

[9] Choi, K., Yu, D. Y., Ahn, S., Kim, K. H., Bang, J. H., and Ko, Y. H. (2018). Joint reliability of various Pb-free solders under harsh vibration conditions for automotive electronics. Microelectronics Reliability, 86, 66-71.

[10] Gharaibeh, M. A. (2021). A simulation-based study on the effect of package parameters on the random vibration behavior of electronic packages. The European Physical Journal Plus, 136(11), 1132.

[11] Hu, X., He, L., Chen, H., Lv, Y., Gao, H., and Liu, J. (2022). The Effect of Electric-Thermal-Vibration Stress Coupling on the Reliability of Sn-Ag-Cu Solder Joints. Journal of Electronic Materials, 51, 284-294.

[12] Muhammad, N., Fang, Z., Shoaib, M. (2020). Remaining useful life (RUL) estimation of electronic solder joints in rugged environment under random vibration. Microelectronics Reliability, 107, 113614.

[13] Che, F.X., and Pang, J.H.L. (2009). Vibration reliability test and finite element analysis for flip chip solder joints, *Microelectronics Reliability 49(7), 754–760.*

[14] Lall, P. and Thomas, T. (2017). PCA and ICA based prognostic health monitoring of electronic assemblies subjected to simultaneous temperature-vibration loads. Proceedings of the ASME 2017 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK2017), 1-12.

[15] Ekpu, M., Bhatti, R., Okereke, M.I., Mallik, S. and Otiba, K. (2014). Fatigue life of lead-free solder thermal interface materials at varying bond line thickness in microelectronics. Microelectronics Reliability, 54, 239-244.

[16] Depiver, J.A., Mallik, S. & Amalu, E.H. (2023). Characterising Solder Materials from Random Vibration Response of Their Interconnects in BGA Packaging. J. Electron. Mater. 52, 4655–4671.

[17] Kumar, P.M., Gergely, G., Horvath, D.K. and Gacsi, Z. (2018). Investigating the Microstructural and Mechanical Properties of Pure Lead-Free Soldering Materials (SAC305 & SAC405). Powder Metallurgy Progress, 18 (1), 049-057.

[18] Ekpu, M. (2019). Finite Element Analysis of the Effect of Fin Geometry on Thermal Performance of Heat Sinks in Microelectronics. J. Appl. Sci. Environ. Manage. 23(11), 2059-2063.