Advanced and Sustainable Technologies (ASET) eISSN 2976-2294
Volume 2, No 1, June 2023 [22-29]

Case Study on Thermal Cycling Analysis for Different Solder Joint Sizes Using Finite Element Analysis

Muhammad Izzuddin Badrol Hissam[1*]

[1]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Perlis, Malaysia.

Received 20 March 2023, Revised 15 May 2023, Accepted 18 May 2023

ABSTRACT

This research uses finite element analysis to investigate the impact of different solder joint sizes on the mechanical aspects. Specifically, a three-dimensional model of a leadless solder joint for surface mount components was created in simulation software. The study analyses lead-free solder joint thermo-mechanical properties, such as maximum stress and strain. The simulation results indicate that the solder joints parameters significantly influence the thermo-mechanical behaviour during temperature cycling tests. The highest stress is observed at the interface between the solder and pad on the large-size solder joint, while the lowest stress (118MPa) is recorded when employing a small-size solder joint. This research contributes to a better understanding the thermo-mechanical characteristics of different solder joint parameters under temperature cycling conditions.

Keywords: Thermal cycling, Solder joint, Finite element analysis, Simulation and modelling

1. INTRODUCTION

Fatigue failure in solder joints is a significant concern in electronic assemblies. This failure is primarily attributed to the stresses and strains arising from thermal mismatch deformation, where different materials expand and contract at different rates under temperature variations [1]. Temperature cycling or thermal cycling tests [2] are commonly conducted in the industry to evaluate the fatigue strength and reliability of solder joints and electronic components. This testing method is widely employed across various sectors due to its relevance in assessing the performance of solder joints and electronic devices under realistic operating conditions [3]. Understanding thermo-mechanical aspects, including thermal stress, strain, and displacement, in solder joints is crucial for advancing electronic technologies. These parameters directly influence solder joints' structural integrity and performance, determining their durability and resistance to failure [4]. By comprehending the thermo-mechanical behaviour of solder joints, researchers and engineers can develop more robust and reliable electronic systems.

Traditional experimental approaches for temperature cycling tests pose certain limitations [5]. They are time-consuming and do not provide real-time visualisation of stress, strain distribution, and displacement within solder joints. This hinders the ability to capture and analyse the dynamic behaviour of solder joints during the temperature cycling process. To overcome these limitations, simulation modelling techniques have emerged as valuable tools in temperature cycling analysis research [6]. By employing simulation models, researchers can simulate and study the thermo-mechanical response of solder joints under various temperature cycling conditions [7], providing detailed insights into their performance and optimising solder joint designs and materials. Using simulation modelling techniques in temperature cycling analysis offers advantages over traditional experimental methods. It enables researchers to explore a wide range of scenarios

---

*Corresponding author: izzuddinangah@gmail.com

efficiently, visualise internal stress and strain distribution, and obtain valuable insights into the behaviour of solder joints under different thermal conditions [8-9].

The widespread adoption of simulation methods underscores their critical role in advancing research and development across various disciplines. Simulation modelling provides an effective and efficient means of comprehending complex processes [10]. Different simulation techniques, including computational fluid dynamics (CFD) [11], finite element (FE) method [12], and finite difference (FD) method, have been extensively employed. Furthermore, the integration of CFD and FE methods has facilitated the resolution of fluid-structural interaction (FSI) [13] and thermal-structural problems [14]. Simulation analysis extends beyond temperature cycling and finds applications in diverse research domains, such as conventional underfill, moulded underfill, integrated circuit encapsulation, reflow soldering, wave soldering processes, and biomedical implant analysis. Moreover, simulation-based optimisation [15] is highly valuable in predicting optimal design and process parameters, aiding in advancing various fields.

This study uses different solder joint sizes to explore the thermo-mechanical characteristics of solder joints. A temperature cycling profile was employed to replicate real-world conditions encountered in temperature cycling tests. The analysis focuses on mechanical aspects throughout the temperature cycling process, including thermal-induced stress, strain, and displacement. To achieve this aim, a three-dimensional model of the solder joint was developed and simulated using software based on the finite element method (FE).

2. MATERIAL AND METHODS

This study focuses on analysing the mechanical behaviour of a leadless solder joint during the temperature cycling process. The simulation specifically assesses thermal-induced stress, strain, and displacement. As depicted in Figure 1, a three-dimensional model was constructed using 3D modelling software. The model comprises a surface mount component, a printed circuit board (PCB), and solder joints on two sides. The surface mount technology (SMT) component is attached and bonded to the printed circuit board (PCB) via the solder joints. The dimensions of the SMT component are 10 mm (L) × 5 mm (W) × 1.2 mm (H), while the PCB measures 20 mm (L) × 15 mm (W) × 1.6 mm (H) [16]. The bottom surface of the PCB was defined as the fixed boundary. The solder joint is assumed to be perfectly bonded to the SMT component and the PCB. The material properties of the solder, PCB, and moulding compound utilised in the 3D model are summarised in Table 1.

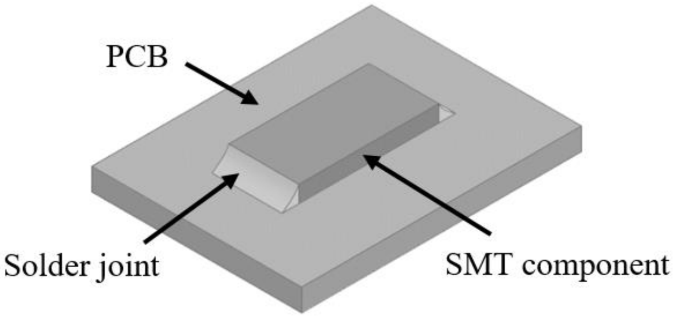

Figure 1: 3D model of the SMT component, solder joint and PCB [16].

Table 1: Material properties used in the simulation [17].

Material	Young Modulus, E (GPa)	Poisson's Ratio	Coefficient of thermal expansion (CTE) ($\times 10^{-6}$/°C)
Sn-58Bi	39.4	0.35	15
PCB (FR-4)	22	0.28	18
Moulding compound	20	0.3	20

The 3D model of the solder joint was meshed using finite element (FE) software, generating approximately 30,000 elements. The solder material Sn-58Bi is considered. This solder material was incorporated into the 3D model of the solder joint, as illustrated in Figure 1. A temperature profile [16] was applied in the simulation to replicate the temperature cycling conditions. The temperature ranged from 120°C to -40°C, with a cycling time of 130 minutes. This temperature profile was used to mimic the temperature cycling environment for the 3D model, ensuring that the solder joint, component, and PCB experienced temperature fluctuations. Subsequently, the simulation results were analysed to determine the maximum thermal-induced stress, strain, and displacement.

Different parameters will affect the thermo-mechanical aspect of thermal cycling temperature. Thus, different heights and diameters will also affect the thermal-mechanical aspects differently. Based on the result of Qi et al. [18], the strain and stress increase as the solder joint's height increases. Height will be on a particular value, whereas stress and strain will nearly keep constant. The higher the solder joints' height, the PCB will fail quickly, according to stress and strain failure standards. Table 2 shows the different solder joint's heights, widths and lengths. These factors analyse the different solder joint parameters towards the thermo-mechanical properties.

Table 2: Solder Joint's height, width and length.

Case	Height (mm)	Width (mm)	Length (mm)
1	1.20	1.20	5
2	1.00	1.00	3
3	1.40	1.40	7

The outcome of the thermo-mechanical aspects during the thermal cycling process is dependent on the solder joint parameters, aligning with the objective of this study. Determining thermal stress and strain is a critical final step among these parameters. For instance, the highest thermal stress indicates unfavourable solder joint conditions, while the lowest thermal stress signifies optimal solder joint conditions, among other factors. The field output assignment allows for the configuration of the desired output reaction.

3. RESULTS AND DISCUSSION

In the context of solder joints, stress and strain play crucial roles in determining their mechanical behaviour and reliability. When exposed to temperature variations during thermal cycling, solder joints experience thermal stress and strain. Thermal stress refers to the internal resistance or force solder joints experience due to temperature changes. Due to the different coefficients of thermal expansion (CTE) between the materials comprising the joint (such as the solder material, component, and PCB), the joint expands or contracts at different rates, leading to thermal stress development. High thermal stress adversely affects the solder joint's structural integrity, potentially leading to fatigue failure or the initiation of cracks.

Thermal strain represents the deformation or shape change within the solder joint due to thermal expansion or contraction. It quantifies the relative change in size or shape of the joint caused by temperature fluctuations. Excessive thermal strain contributes to stress concentrations, further escalating the risk of failure or damage within the joint.

The case 1 solder joint data corresponds to the Sn-58Bi solder material, with the solder joint being standard size. The results data, encompassing the maximum thermal stress and thermal strain values, are summarised in Table 3 for reference and analysis. Table 3 presents a comprehensive overview of the observed maximum stress and strain for the solder joint under investigation.

Table 3: Thermo-mechanical aspects of a normal-size solder joint.

Parameter	Minimum	Maximum
Stress	0	195.441MPa
Strain	-377.418×10^{-6}	3.127×10^{-3}

Understanding and analysing the magnitude and distribution of thermal stress and strain in solder joints is crucial for assessing their performance, reliability, and lifespan. By examining these parameters, researchers and engineers can identify potential weak points or areas of concern within the solder joint design. This allows for the optimisation of materials, dimensions, and manufacturing processes to enhance the solder joint's durability and resistance to failure.

These stress and strain analyses are typically conducted using simulation techniques such as the finite element method (FEM), which allows for the accurate prediction and visualisation of the solder joint's mechanical behaviour under varying thermal conditions. By evaluating the stress and strain distribution, researchers can gain insights into the solder joint's performance and potential failure mechanisms, enabling them to make informed decisions regarding design improvements or material selection to enhance its overall reliability.

In Case 2, the solder joint has a small size for the Sn-58Bi. The data for this solder joint is shown in Table 4. The stress distribution data is shown in Figure 2. The maximum stress of the solder joint is at the edge of the solder joint, which is between the PCB and the chip resistor. The maximum value of the thermal stress is 118.914 MPa. The maximum thermal stress value does not exceed the maximum thermal stress of the standard-size solder joint. This result shows that the small size affects the solder joint's thermo-mechanical aspects and fatigue life.

Table 4: Thermo-mechanical aspects of the small-size solder joint.

Parameter	Minimum	Maximum
Stress	0	118.914 MPa
Strain	-197.023×10^{-6}	1.804×10^{-3}

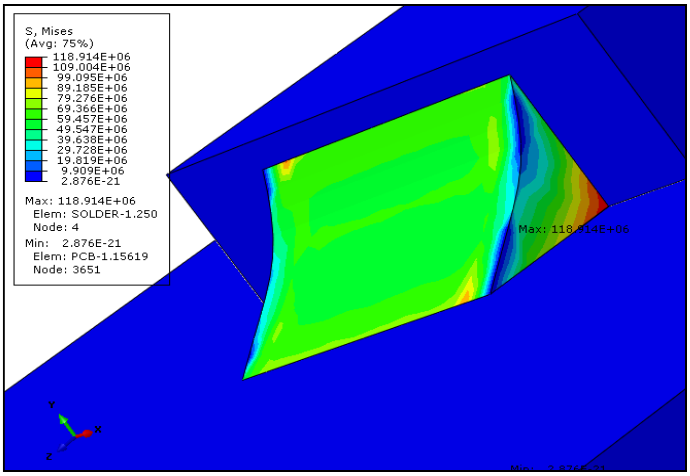

Figure 2: Thermal stress of a small-size solder joint.

Figure 3 illustrates the distribution data portraying the thermal strain characteristics of the small-sized solder joint. Notably, the elevated strain is predominantly concentrated along the edges of the solder joint. At the location exhibiting the highest thermal stress, the solder joint also experiences the maximum thermal strain, measured at 1.804×10^{-3}. Previous research by Hu et al. [19] indicates an increase in both absolute shear stress and shear strain, which subsequently impacts the length and thickness of the solder joint. This alteration can lead to an overall increase in the joint's dimensions and a decrease in its thermal fatigue life. Additionally, Mercado et al. [20] concluded that employing a thicker substrate enhances the stiffness of the package, thereby extending the fatigue life. Moreover, an elongated substrate undergoes more severe warping at high temperatures, exposing the solder joint to significant stress and inducing shear stress in the x direction.

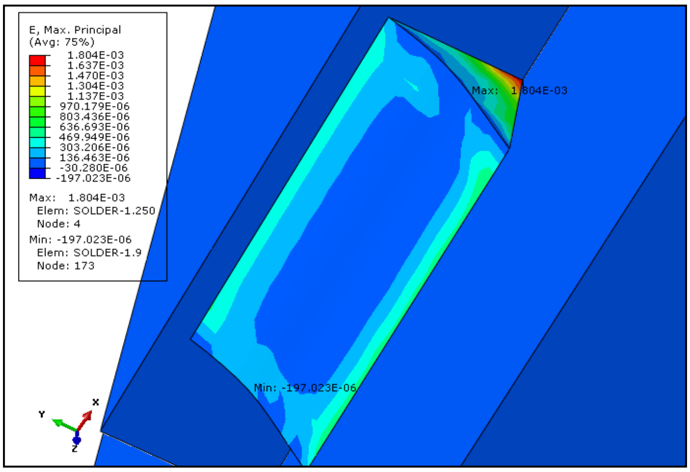

Figure 3: Thermal strain of the small solder joint.

Case 3 is the large-size solder joint. The data is shown in Table 5. The thermal stress and strain distribution data are shown in Figures 4 and 5. Figure 6 shows the comparison of stress and strain for different sizes of solder joints. The maximum stress of the solder joint is concentrated at the left side of the solder joint, with a maximum stress value of 406.330 Mpa. The value exceeds both the small-size and the normal-size solder joint. The current results revealed that the thermal stress and strain would increase as the solder joint's length and thickness increase. As the size increases, the solder joint will sustain more stress. Figure 5 illustrates the thermal strain of the large-size solder joint. The strain of the solder joint is separated at all solder joints but is concentrated more on the base of the solder joint. This is because it is attached above the PCB, the fixed part that causes stress to the solder joint. The maximum value of the solder joint is $5.204\times10^{-3,}$ which is at the side of the solder joint.

Table 5: Thermo-mechanical aspects of a large-size solder joint

Parameter	Minimum	Maximum
Stress	0	406.330 MPa
Strain	-197.023×10^{-6}	5.204×10^{-3}

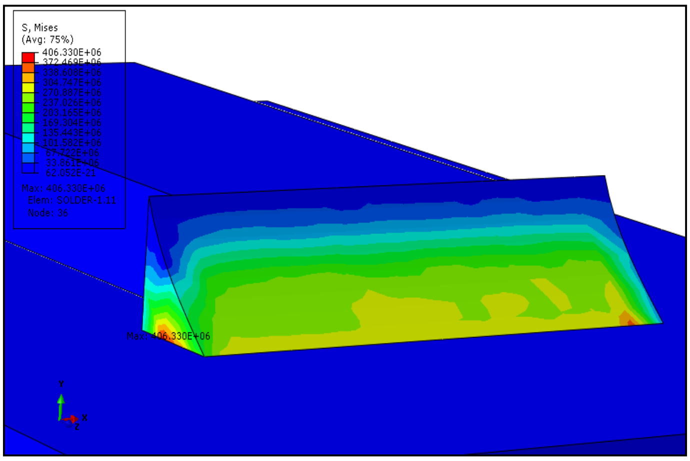

Figure 4: Thermal stress of a large size solder joint.

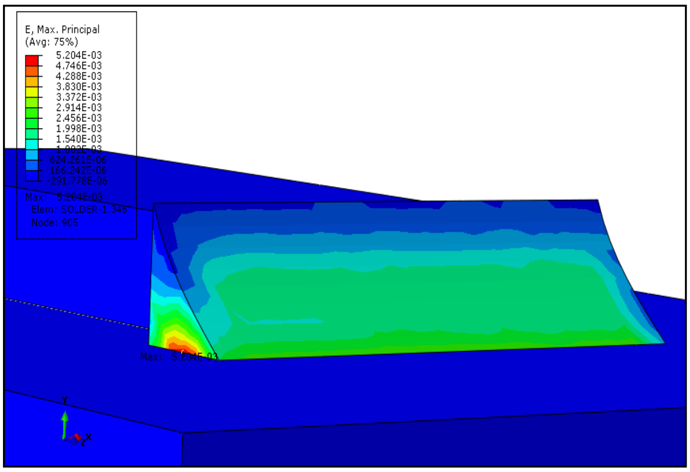

Figure 5: Thermal strain of the large-size solder joint.

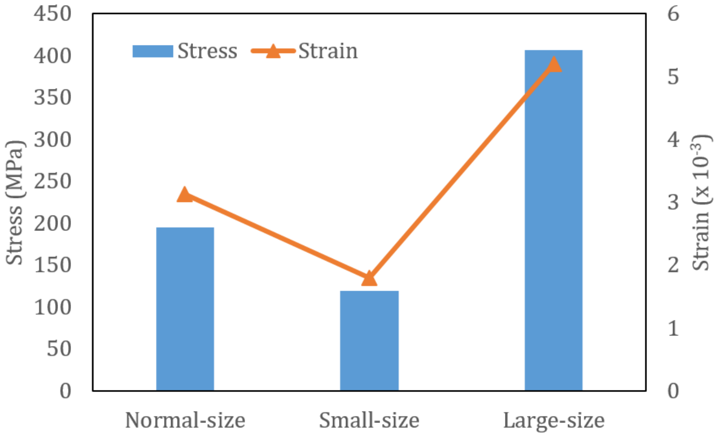

Figure 6: Comparison between cases of stress and strain.

Several potential consequences can arise when the solder joint experiences high stress, such as fatigue failure, damage, increased risk of solder joint failure, reduced reliability and temperature gradient issues. High thermal stress accelerates fatigue failure in the solder joint. The repeated expansion and contraction caused by temperature variations lead to the initiation and propagation of cracks, eventually failing the joint. Besides, excessive thermal stress would cause permanent deformation or damage to the solder joint, compromising its structural integrity. This damage can lead to solder joint displacement, misalignment, or detachment from the components or PCB. Moreover, the high thermal stress significantly weakens the solder joint, making it more susceptible to external stressors or mechanical loads. It may increase the likelihood of failure under normal operating conditions, such as vibration, shock, or thermal cycling. High thermal stress on a small-sized solder joint can decrease its overall reliability. The joint may be more prone to premature failure or degradation, impacting the electronic device's or assembly's performance and functionality. High thermal stress also contributes to temperature gradient-related problems within the solder joint. It leads to uneven heating or cooling across the joint, resulting in non-uniform expansion or contraction and causing localised stress concentrations.

4. CONCLUSION

This study utilised the finite element method to conduct a comprehensive thermo-mechanical analysis of various solder materials, specifically focusing on Sn-58Bi solder. The simulation results revealed that the size of the solder joint played a crucial role in determining its thermo-mechanical behaviour. As the temperature cycling, the solder joint experienced expansion and contraction, generating thermal stress. The simulation outcomes demonstrated that the highest stress concentrations occurred at the contact region between the solder joint, component, and PCB. Among the different solder joint sizes investigated, the small solder joint exhibited the lowest stress levels (118 MPa) and strain (1.804×10^{-3}). Minimising stress and strain can mitigate the risk of crack formation and propagation in prolonged thermal environments. To further advance knowledge in this field, future studies could explore alternative temperature cycling profiles and consider different types of solder joints.

ACKNOWLEDGEMENTS

The author gratefully thanks the staff of the Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), for the technical support.

REFERENCES

[1] Depiver, J. A., Mallik, S., & Harmanto, D. Solder joint failures under thermo-mechanical loading conditions–A review. Advances in Materials and Processing Technologies, vol 7, issue 1 (2021) pp. 1-26.

[2] Depiver, J. A., Mallik, S., & Amalu, E. H. Thermal fatigue life of ball grid array (BGA) solder joints made from different alloy compositions. Engineering Failure Analysis, vol 125, (2021) p. 105447.

[3] Jiao, Y., Jermsittiparsert, K., Krasnopevtsev, A. Y., Yousif, Q. A., & Salmani, M. Interaction of thermal cycling and electric current on reliability of solder joints in different solder balls. Materials Research Express, vol 6, issue 10 (2019) p. 106302.

[4] Tan, J. S., Khor, C. Y., Rahim, W. M. F. W. A., Ishak, M. I., Rosli, M. U., Jamalludin, M. R., ... & Ani, F. C. Influence of solder joint length to the mechanical aspect during the thermal stress analysis. In AIP conference proceedings, vol 1885, issue 1 (2017) p. 020063.

[5] Chen, J., Xie, Y., He, Z., Wan, N., & Wu, Y. Analysis on the Thermal Fatigue Behavior of Single SnAgCu Solder Joint. In 2019 20th International Conference on Electronic Packaging Technology (ICEPT) (2019) pp. 1-4.

[6] Qiu, B., Xiong, J., Wang, H., Zhou, S., Yang, X., Lin, Z., ... & Cai, N. Survey on Fatigue Life Prediction of BGA Solder Joints. Electronics, vol 11, issue 4 (2022) p. 542.

[7] Zarmai, M. T., & Oduoza, C. F. Impact of inter-metallic compound thickness on thermo-mechanical reliability of solder joints in solar cell assembly. Microelectronics Reliability, vol 116, (2021) p. 14008.

[8] Nivelle, P., Tsanakas, J. A., Poortmans, J., & Daenen, M. Stress and strain within photovoltaic modules using the finite element method: A critical review. Renewable and Sustainable Energy Reviews, vol 145, (2021) p. 111022.

[9] Long, X., Su, T., Lu, C., Wang, S., Huang, J., & Chang, C. An insight into dynamic properties of SAC305 lead-free solder under high strain rates and high temperatures. International Journal of Impact Engineering, vol 175, (2023) p.104542.

[10] Jansaengsuk, T., Pattanapichai, S., & Thongsri, J. A Development of an Induction Heating Process for a Jewelry Factory: Experiments and Multiphysics. Processes, vol 11, issue 3 (2023) p. 858.

[11] Zheng, Y., Fang, J., Wei, L., Shen, H., & Gong, Y. Shape prediction of the BGA solder joint in hot air reflow soldering based on CFD. In MEMAT 2022; 2nd International Conference on Mechanical Engineering, Intelligent Manufacturing and Automation Technology, (2022) pp. 1-5.

[12] Jayesh, S., & Elias, J. Finite element modeling and random vibration analysis of BGA electronic package soldered using lead free solder alloy– Sn-1Cu-1Ni-1Ag. International Journal for Simulation and Multidisciplinary Design Optimization, vol 10, (2019).

[13] Khor, C. Y., & Abdullah, M. Z. Analysis of fluid/structure interaction: Influence of silicon chip thickness in moulded packaging. Microelectronics Reliability, vol 53, issue 2 (2013) pp. 334-347.

[14] Sharizal Abdul Aziz, M., Zulkifly Abdullah, M., & Yee Khor, C. Influence of PTH offset angle in wave soldering with thermal-coupling method. Soldering & Surface Mount Technology, vol 26, issue 3 (2014) pp. 97-109.

[15] Leong, W. C., Abdullah, M. Z., & Khor, C. Y. Optimization of flexible printed circuit board electronics in the flow environment using response surface methodology. Microelectronics Reliability, vol 53, issue 12 (2013) pp. 1996-2004.

[16] Khor, C. Y., Termizi, S. N. A., Ishak, M. I., Hissam, M. I. B., & Ani, F. C. Thermo-mechanical analysis of various solder materials via finite element method. In AIP Conference Proceedings, vol 2291, issue 1, (2020) p. 020055.

[17] Tan, J. S., Khor, C. Y., Lau, C. S., Ani, F. C., Tan, W. H., & Chuah, H. G. Influence of surface mount solder joint height during the thermo-mechanical analysis. In AIP Conference Proceedings, vol 2030, issue 1 (2018) p. 020127.

[18] Qi, X., Zhou, B., & En, Y. Effect of solder joint parameter on vibration fatigue reliability of high density PCB assembly. In 2011 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering, (2011) pp. 514-517.

[19] Hu, B., Zhou, J., Zhou, P., & Yang, Y. The effect of accelerated thermal cycle parameters and the geometry dimensions on solder joint reliability. In Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, (2006) pp. 242-246).

[20] Mercado, L. L., Sarihan, V., Guo, Y., & Mawer, A. Impact of solder pad size on solder joint reliability in flip chip PBGA packages. IEEE Transactions on Advanced Packaging, vol 23, issue 3 (2000) pp. 415-420.