IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

Determination of stress and strain in printed circuit boards
Doctoral Thesis – Abstract
for obtaining the scientific title of doctor at
Polytechnic University of Timisoara
in the doctoral field of Mechanical Engineering
author ing.Alexandru Falk
scientific supervisor Univ. Dr. Eng Liviu Marșavina and Univ. Dr. Eng Ioan Octavian Pop
month 11 year 2022

In recent years, the rapid development of the global electronic industry has gradually increased the market demand for electronic products with various functions, so printed circuit boards (PCBs) must be installed with more features or miniaturized without sacrificing functionality. By restricting the use of conventional solders containing lead, they have been replaced by lead-free Sn-Ag Cu (SAC) alloys which are more brittle.

The coefficients of thermal expansion (CTE) of the different materials on the PCB lead to variation in the level of thermal expansion, resulting in stresse and strain. Additionally, the testing and case assembly processes can induce additional stresses in the PCB, causing cracks in the solder paste. The main components affected are microprocessors due to the way they are soldered onto PCBs with balls of solder paste (BGA - Ball grid array), Huang et al. (2011), Huang et al. (2016), Sitek et al. (2004), Huang (2015).

That is why the control of strain on PCBs is very important, currently the limit used in the automotive industry according to IPC JEDEC-9704 is 700 microstrain (μm/m) (specific deformation expressed in terms of parts per million, 10^(-6)) for the PCB used in this study with a thickness of 1.6mm.

Currently, the measuring method with strain gauges is used. This method allows the determination of strain only at certain points. But it is important to know the strain distribution specifically over the entire surface of the PCB to avoid positioning critical electronic components such as microprocessors. For this reason, a new methodology was chosen to determine the strain on the entire surface called the digital image correlation method, which is a non-contact optical measurement method.

Thus, thesis aims to bring into discussion a new method for determining the state of deformation in PCBs with the help of digital image correlation, the possibility of developing some methodologies for determining the state of stress and deformation in PCBs and validation of finite element simulations. Also, with the help of FEA, additional information can be obtained such as the distribution of the equivalent stress over the entire surface of the PCB and the singular stress field at the PCB-BGA interface.

In the first chapter, ***Introduction***, a presentation of printed circuit boards (PCBs) and their role is given first. It also presents the main problems that can occur and which are the main affected components, which are the microprocessors due to the way they are glued to the PCBs with the help of solder paste balls (BGA - Ball grid array). For this reason it is very important to know the distribution of strain over the whole surface of the PCB. Then a review is made of the current method of measuring strain, the resistive strain gauge method, respectively the digital image correlation method is a non-contact optical measurement method for measuring specific strains on the entire surface.

The second chapter, with the title ***Current status regarding the determination of deformations in PCBs***, presents the method of resistive strain gauge and the applicability of this method for the determination of strain on PCBs. This method allows the determination of strain only at certain points.

For the measurement of strain, the most used strain gauges used in practice are in the form of a rosette consisting of three strain gauges positioned at a certain angle (0° -45° -90°; 0° -60° -120°), Omega engineering (1999), Intel (2016), Bin and Ueda (2011), IPC (2012), National Instrument (2016).

In accordance with the IPC standard, it is presented how to arrange the tensometric rosettes on the PCB and how to prepare the surface of the PCB in order to obtain reliable results. From the presented applications it could be seen that the place where the tesometric rosettes are placed is very important. Placing the strain gauge too close to the corner of the electronic component causes the measurement to be very sensitive to small strain gauge placement errors. Placing the strain gauge too far from the corner of the electronic component results in reduced sensitivity to the true deformation in the corner of the component. Thus, in the case of microprocessors, the recommended distance for placing the tensometric rosettes is 3.6 ±0.5 mm from the edges of the component, Intel (2016), Bin, H. and Ueda, T. (2011), Chvojan, J. and Vaclavik, J. (2018).

The finite element analysis (FEA) method is also presented in this chapter. FEA being very helpful in finding out the areas where problems may occur before the product is built. This information is used to make product design adjustments to reduce strain and to reposition certain sensitive electronic components (eg microprocessors) if necessary. According to the presented applications the long time required to build and solve the models cannot be justified when only PCB analysis is required. Thus models can be defined that use simple 3D block elements to recreate component effects, stiffness and added mass. Many good examples of detailed finite element models already exist in the current literature. Dehbi et al. (2005), Gu et al. (2007), Chen et al. (2008), Luan et al. (2006), Shetty et al. (2001), Shetty et al. (2003), Li et al. (2001), Jih et al. (1998), in which the complexity of these models is justified as it is necessary to determine the internal stresses of the components.

The third chapter, entitled ***Experimental determination of strain***, presents the PCB assembly configuration used for the experimental determination of strain using the resistive strain gauge method, respectively the digital image correlation method. Two types of loading were considered to see the influence of bumps in the distribution of specific principal strains. Case 1 considered bumps on the housing and cover and in case 2 only bumps on the housing were considered. The PCB is assembled between the housing and the cover using four M2.5 screws, using a maximum torque of 0.7Nm.

The measurements in this chapter were carried out in the Mechanics and Strength of Materials laboratory of the University Politehnica Timisoara.

For the measurements made with the strain gauges, three areas on the PCB were taken into account at the corners of the microprocessor, where the strain gauge rosettes were placed and the strain were measured. The strain gauge used is HBM RF91 with the following characteristics: 120 Ω resistance, three strain gauge marks located at: 0°, 45°, 90°. Data acquisition was done with QuantumX MX1615B and analyzed with Catman Easy V5.3.1 software. Following the analysis of the obtained results, it was observed that in the case of tensometric rosette 1, the maximum principal strain exceeds the admissible value of 700 μm/m. This is caused by the level difference produced by the bumps present near the microprocessor.

For the measurements made using the digital image correlation method, the equipment used for capturing and processing the images was the Dantec Q-400 system. The two cameras of the Q-400 correlation system are set to a resolution of 5 megapixels. In order to properly acquire and process the images, a random speckle pattern had to be applied to the PCB surface first. This was done by applying a black spray paint over a uniform white layer.

Studies show that this method is used as documented in a lot of applications such as: measuring large strains Tarigopula et al. (2008), the crack analysis of Tung et al. (2008), definition of (σ-ε) diagrams for new materials Mol'kov and Yu (2013), constructions – to evaluate certain displacements and cracks Cheng et al. (2017), Li et al. (2017), measuring strains caused by temperature variations Wang and Pan (2016), Ramosa et al. (2015). Pan et al. (2014)., Tekieli et al. (2017), Hild and Roux (2006), Malesa et al (2013).

After image capture, correlation and analysis were done with Istra 4D software. The analysis of strain was performed in the region of interest (ROI) defined on the surface of the PCB.

According to the DIC principle, this region was divided into small subsets. Displacement and strain fields were calculated in these subsets using a correlation algorithm. The obtained results describe the global behavior of the PCB. This analysis reveals that in "loading case 1", higher specific strains are observed on the PCB surface than in "loading case 2". These results clearly show the influence of the housing and cover geometry on the strain distribution. It can be seen that the maximum specific strain exceeds the value of 700 μm/m in the areas with bumps in both cases.

For a better understanding of the results, virtual optical strain gauges (A1-A2, B1-B2, C1-C2;, D1-D2) were used to calculate the local maximum principal strain and also to be able to compare the results with obtained from measurements made with the help of strain gauges, respectively FEA. Thus in area D1-D2 the value of 700 μm/m is exceeded in both loading cases, the maximum value recorded being 1039 μm/m for loading case 2. For areas A1-A2, B1-B2 and C1-C2, the values strain are less than 700 μm/m for both loading cases.

The fourth chapter, called ***Numerical determination of strain on the PCB***, presents the results obtained with the help of numerical models. FEA is very helpful in finding areas where problems may occur before the product is built. In the case of PCBs this information is used to make product design adjustments to reduce strain and to reposition certain sensitive electronic components (eg microprocessors) if necessary.

The commercial software Ansys Workbench 18.1 was used for the finite element analysis. To simplify the model, the electronic components were considered as simple geometric blocks with a generic material (a hard plastic) assigned and for the PCB an FR4 material with orthotropic properties determined experimentally by the PCB supplier was assigned in the first simulation and in the second simulation, an FR4 material from the Ansys material property database and for the housings an aluminum alloy. Boundary conditions were applied to the screws in the form of a screw pretension of 1800 N equivalent to 0.7 Nm, this value is in accordance with the data received from the screw supplier based on simulations. After performing the discretization, a total number of 80254 tetrahedral elements, connected in 266649 nodes, was obtained.

Following the obtained results, it can be observed that the maximum strains are located near the large component (microprocessor) and near the fixing holes, the maximum strains are above the permissible value (700 μm/m). As with the digital image correlation method, for a good understanding of the distribution of the maximum principal specific strains in the area of the microprocessor, the results were interrogated according to segments A1-A2, B1-B2, C1-C2, D1-D2. Thus in the area D1-D2 the value of 700 μm/m is exceeded both for case 1 and for case 2, the maximum recorded value being 1018 μm/m for loading case 1 and 884 for loading case 2.

The difference between the simulation results with the experimentally determined FR4 material properties and the predefined properties in Ansys is below 2%.

The results for the distribution of the allowable stress over the entire surface of the PCB were also obtained, thus it could be observed that the value of the allowable stress of 270 Mpa for the PCB material is not exceeded in both loading cases.

Chapter five, entitled ***Temperature Influence on PCB Deformation***, presents the analysis of temperature influence on the evolution of maximum principal strain on PCBs. For this, two experimental methods were used, the resistive strain gauge method and the Digital Image Correlation method, supplemented with numerical modeling and simulation by the finite element method using the Ansys Workbench 18.1 software.

One of the main causes of failure in electronic assemblies is the thermo-mechanical deformation experienced during thermal expansion. Defects such as cracks of BGAs, traces, debonding of components are caused by thermal stresses due to different coefficients of thermal expansion. Understanding the state of stress and strain induced on the PCB due to temperature variations is important to predict reliability.

The measurements in this chapter were carried out in the Egleton Laboratory of Civil Engineering and Sustainable Construction of the University of Limoges.

For the measurements made with the strain gauges, two areas on the PCB from the corners of the microprocessor were taken into account, where the strain gauge rosettes were placed and the strain was measured. The experimental setup, included the PCB, oven and data acquisition system. Data acquisition was performed with the Spider 8 system and analyzed with Catman Easy V5.3.1 software. To examine the evolution of strain as a function of temperature, the PCB was placed in an oven and the temperature was changed in several steps: 25, 50, 85 and 120 °C. The strain gauges used were Kyowa KFGS-1-120-D17-11 (right angle gauge) with the following characteristics: resistance 120 Ω, three strain gauge marks placed at 0°, 45° and 90°. Temperature compensation was done by inserting an unsolicited PCB into the oven.

Following the analysis of the results, it was possible to observe the increase of the maximum principal strain with the increase of the temperature. At each temperature interval at the beginning of the period the strains increase and then stabilize at the end of the holding interval. The maximum principal strain exceeds the limit of 700 μm/m during temperature range

3 (85 °C).

For the measurements made using the digital image correlation method, the experimental setup was composed of the PCB assembly, the oven and the CCD camera. The software used for image acquisition was Trasse ANDRA3 and for Digital Image Correlation Correla developed by the University of Poitiers. The analysis of strain was performed in the region of interest (ROI) defined on the surface of the PCB. According to the DIC principle, this region was divided into small subsets. Displacement and specific strain fields were calculated in these subsets using a correlation algorithm. As with the mechanical strain, virtual optical strain gauges (A1-A2, B1-B2) were used to calculate local specific strains. The optical strain gauge positions are in the same region as the finite element analysis segments and strain gauges. The idea is to compare the results obtained in the finite element analysis with the experimental measures using the same setup.

Following the analysis of the results, it was possible to observe the increase in the maximum main specific deformation with the increase in temperature for each temperature step. The maximum principal strain exceeds the limit of 700 μm/m during temperature range 3 (85 °C) in both interrogated areas.

For the finite element analysis, as in the case of the model used for mechanical stress, to simplify the model, the electronic components were considered as simple blocks of geometry with a generic material (a hard plastic) assigned and the PCB was assigned FR4 material with orthotropic properties. The boundary conditions applied are: for the bolts, a bolt pretension of 1800 N equivalent to a tightening torque of 0.7 Nm was applied, this value is in accordance with the data received from the bolt supplier based on simulations, and the temperature in several stages: 25, 50, 85 and 120 °C.

After performing the discretization, a total number of 80254 tetrahedral elements, connected in 266649 nodes, was obtained. By solving the finite element model, the distribution of the maximum strains on the PCB was obtained. As with the digital image correlation method, for a good understanding of the distribution of the maximum principal specific strains in the area of the microprocessor, the results were interrogated according to segments A1-A2 and B1-B2. It is observed that the maximum principal strain increases with increasing temperature for each temperature step. The maximum principal strain exceeds the limit of 700 μm/m during temperature range 3 (85 °C) in both interrogated areas.

The results for the allowable stress distribution over the entire surface of the PCB were also obtained. It can be seen that the maximum equivalent stress values are located near the large component (microprocessor) and near the mounting holes. The maximum value of the equivalent stress being below the value of the maximum allowable stress of 270 Mpa in all 4 temperature cases.

In the sixth chapter, with the title ***Analysis of the obtained results***, it presents the comparison of the results obtained in the case of mechanical and thermal stresses with the two experimental methods, the resistive strain gauge method and the Digital Image Correlation method, respectively numerical simulation using the finite element method.

In the case of mechanical stress, by comparing the obtained results, it could be observed that the results obtained by the Digital Image Correlation method are within the limits of the results obtained from the measurements with strain gauges, which are comparable to the results obtained from the simulations with finite elements. The limit of admissible strain of 700 μm/m being exceeded for both evaluation approaches in the D1-D2 area.

In the case of thermal stress, it could be observed that the results obtained by the Digital Image Correlation method are in good agreement with the results obtained from measurements with strain gauges. For region 0 (A1-A2 and strain gauge 0), the maximum difference of 30.4% is at 50 °C and for region 1, the maximum difference of 12.5% is at 50 °C. It can also be observed that the results obtained by the Digital Image Correlation method are in the same range as the results obtained from the finite element analysis. For the A1-A2 area, slightly larger differences can be observed at 50 °C, where the maximum difference is 16.8% and at 120 °C it is 14.1%. For the B1-B2 area, slightly larger differences can be observed at 120 °C, where the maximum difference is 22.6%.

In the conclusions of this chapter, it can be seen that the results obtained are relatively close. Thus, the digital image correlation method can be validated as a method for investigating deformations in mechanically and/or thermally stressed PCBs. The advantage of this method compared to the resistive electric tesometry method is that it is a non-contact method, not modifying the rigidity of the PCB by attaching tensometric rosettes, respectively it is a "full field" method that allows the determination of stresses and deformations on the entire surface of the PCB, in comparison with tensometric measurements that give the results of point deformations in the area of the tensometric rosette.

Chapter seven, entitled ***The singular stress field at the PCB-BGA interface***, presents the singularity of the stress field at the interface of two materials. Finite element analysis was used for the singularity analysis at the PCB-BGA interface and the commercial software Ansys Workbench 18.1 was used. The interface between the PCB and a ball of solder paste was considered, and as a boundary condition a displacement of 0.05mm. The materials used being the same as in the previous finite element analises.

Following the finite element analysis, the distribution of the maximum stress over the entire surface of the ball was obtained. From which it could be observed that the maximum stress values occur at the beginning of the interface notch between the PCB and the solder paste. In order to highlight the behavior at the end of the interface, the results of the stresses were queried depending on the distance r=0.02mm for five different values of the angle θ-0°, 30°, 45°, 60° and 90°. Representing on a logarithmic scale the stress variations depending on the distance r and performing a linear interpolation of the graph logσ=f(logr) the slope of the line is equal to λ-1, an average value of the singularity order λmed=0.48 was obtained. With the help of mathcad (Appendix 1), the analytical value of the singularity of the stress field was calculated, obtaining a value of 0.474.

In the eighth chapter, **Conclusions and personal contributions**, the general conclusions, personal contributions and some prospects for further development of the research undertaken in the doctoral thesis were presented.

The obtained results were disseminated in several scientific papers, indexed Web of Science-WoS (ISI):

1. A. Falk, L. Marsavina, O. Pop, "Analysis of Printed Circuit Boards strains using finite element analysis and digital image correlation", FRATTURA ED INTEGRITA STRUTTURALE, Vol. 51, pp.541-551, Jan. 2020 (WOS:000502844600041)

2. A. Falk, L. Marsavina, O. Pop, J. Dopeux "Assessment of Strains Produced by Thermal Expansion in Printed Circuit Boards", Materials, Vol. 15(11), art. 3916, May 2022

(WOS:000809023200001)

3. A. Falk, L. Marsavina, O. Pop, "Experimental determination of strain distribution on Printed Circuit Boards using Digital image correlation", 25th International Conference on Fracture and Structural Integrity, Vol. 18, pp. 214-222, 2019 (WOS:000504238000023)

Bibliografie

Bin, H. and Ueda, T. , 2011, Investigation on the optimum sampling rate of strain measurement during printed circuit board (PCB) system assembly, 13th Electronics Packaging Technology Conference p.579-584

Chen Y, Wang C, Yang Y., 2008, Combining vibration test with finite element analysis for the fatigue life estimation of PBGA components. Microelectron Reliab;48(4):638–44.

Cheng, J.-L., Yang, S.-Q., Chen, K., Ma, D., Li, F.-Y., & Wang, L.-M., 2017, Uniaxial experimental study of the acoustic emission and deformation behavior of composite rock based on 3D digital image correlation (DIC). Acta Mechanica Sinica, 33(6), 999–1021.

Chvojan J. and Vaclavik J., 2018, PCB Tests during Assembly and Splitting,Proceedings,2, 472

Dehbi A, Ousten Y, Danto Y, Wondrak W. , 2005, Vibration lifetime modelling of PCB assemblies using Steinberg model. Microelectron Reliab;45(9–11):1658–61.

Gu J, Barker D, Pecht M., 2007, Prognostics implementation of electronics under vibration loading. Microelectron Reliab;47(12):1849–56.

Hild, F., Roux,S.,2006, Digital Image Correlation: from Displacement Measurement to Identification of Elastic Properties – a Review, Journal compilation 42 p.69-80

Huang C.Y. , Lin Y.H. , Ying K.C., Ku C.L., 2011, The solder paste printing process: critical parameters,B27+B1:B21+B1:B23+B27+B1:B21+B1:B24+B1:B22+B1:B21+B1:B22

Huang C.Y. , . Chen C.H, Lin Y.H., 2016, A grey-ANN approach for optimizing the QFN component assembly process for smart phone application, Solder. Surface Mount Technol. 28 (2) 63–73."

Huang C.Y., 2015, Innovative parametric design for environmentally conscious adhesive dispensing process, J. Intell. Manuf. 26 (1) 1–12.

Intel, 2016 Intel Strain Measument methodology for Circuit Board Assembly- Board Flexure Initiative (BFI)

IPC, IPC JEDEC 9704A, 2012
Jih E, Jung W., 1998, Vibrational fatigue of surface mount solder joints, ITherm'98. In: Sixth intersociety conference on thermal and thermomechanical phenomena in electronic systems (Cat. No. 98CH36208),. p. 246–50.
Li R., 2001, A methodology for fatigue prediction of electronic components under random vibration load. ASME J Electron Packag,123(4):394–400
Luan J, Tee TY, Pek E, Lim CT, Zhong Z, Zhou J., 2006, Advanced numerical and experimental techniques for analysis of dynamic responses and solder joint reliability during drop impact. IEEE Trans Compon Packag Technol;29(3):449–56.
Malesa,M., Malowany,K. , Tomczak ,Ur., Siwek ,B. , Kujawinska, Lewandowska, A. S., 2013, Application of 3D digital image correlation in maintenance and process control in industry, Computers in Industry 64 p.1301-1315
Mol'kov,V.,Yu, , 2013, Application of the method of digital image correlation to the construction of stress strain diagram, Vol. 48, No. 6 p.832-837
National Instrument, 2016, Engineer's Guide to Accurate Sensor Measurements (National Instrument)
Omega engineering, 1999, Practical Strain Gage measurements
Pan,B., Yuan, J., Xi,Y. , 2014, Strain field denoising for digital image correlation using a regularized cost function, Optics and Lasers in Engineering 65 p.9–17
Ramosa,T., Furtado,A., Eslami,S., Alves, S., Rodrigues,H., Arêde, A., Tavares, P. J. , Moreira, P. M. G. P., 2015, 2D and 3D Digital Image Correlation in Civil Engineering – Measurements in a Masonry Wall, Procedia Engineering 114 p.215-222
Shetty S, Lehtinen V, Dasgupta A, Halkola V, Reinikainen T., 2001, Fatigue of chip scale package interconnects due to cyclic bending. ASME J Electron Packag,123(3):302–8.
Sitek J., Rocak D. , Bukat K. , 2004, A comparison of the quality of lead-free solder pastes, Solder. Surface Mount Technol. 16 (2) 22–30."
Tarigopula V., Hopperstad O.S., Langseth M., Clausen A.H., Hild F., Lademo O.-G., Eriksson M., 2008, A Study of Large Plastic Deformations in Dual Phase Steel Using Digital Image Correlation and FE Analysis, Experimental Mechanics 48:181–196
Tekieli, M., De Santis,S., de Felice,G., Kwiecien,A., Roscini,F., 2017, Application of Digital Image Correlation to composite reinforcements testing, Composite Structures 160 p.670–688
TUNG, S.H., SHIH, M.H, SUNG, W.P., 2008, Development of digital image correlation method to analyse crack variations of masonry wall, Sadhana Vol. 33, Part 6 p.767-779
Wang, B., Pan, B., 2016, Subset-based local vs. finite element-based global digital image correlation: A comparison study, Theoretical & Applied Mechanics Letters 6 p.200-208