

Article

Measurements of Thermally-Induced Curvatures and Warpages of Printed Circuit Board during a Solder Reflow Process Using Strain Gauges [†]

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Abstract: Measurements of the curvatures and warpages of a printed circuit board (PCB) during a thermal solder reflow process using strain gauges are proposed in this study. In the experiments, a shadow moiré is used for measuring the out-of-plane deformations (or warpage) of a bi-material plate and a PCB with dual in-line memory module (DIMM) sockets during solder reflow heating, while the finite element method (FEM) is used to analyze the thermally-induced deformation of the PCB specimen for ensuring the validity of the measurement. Conventional strain gauges are employed to measure the strains (albeit as in-plane strain data) in both specimens during the solder reflow process. The results indicate that the strain gauge-measured strain data from the top and bottom surfaces of both specimens during the solder reflow can be converted into curvature data with specific equations, and even into global out-of-plane deformations or warpages with a proposed simple beam model. Such results are also consistent with those from the shadow moiré and FEM. Therefore, it has been proved that the strain gauge measurement associated with the simple beam model can provide a method for the real-time monitoring of PCB deformations or warpages with different temperatures during the solder reflow process.

Keywords: strain gauge; shadow moiré; warpage; printed circuit board; solder reflow; finite element method

1. Introduction

Surface mount technology (SMT) is now a widely-used method for mounting discrete electronic components (or packages) on a printed circuit board (PCB) to interconnect with smaller-size and finer-pitch components using the solder joints. To implement the SMT, an infrared (IR) solder reflow process with well-controlled heating and cooling temperatures has been used for mounting the electronic components on the PCB with solder joints (or paste). However, there exists a problem with PCB warpage in such device assembly during the solder reflow process. The excessive warpage of the PCB would result in some solder joint defects, such as short or open circuits, or thermal-mechanical strains in the PCB, seriously influencing the reliability of the PCB assembly [1]. The main factor causing the thermal-mechanical strains is a coefficient of thermal expansion (CTE) mismatch between the electronic components and the PCB, which would have a great deal of influence on the reliability of solder joints in microelectronic packages [2]. Therefore, methods to effectively measure and further

control or even reduce the PCB warpage in the reflow process are of utmost importance. In 1997, a real-time strain-gauge probe method for measuring and recording the in-process deformation of packages during a simulated solder reflow process was developed [3]. Strain gauges have been widely used in measuring the mechanical strain on a PCB due to their reliable and easy-to-use characteristics. Appropriately selected locations adhered with a strain gauge are very important for accurately measuring the strains on packages [4]. A method for evaluating the strain gauges used in printed circuit board assemblies was proposed for mechanical strain monitoring [5]. Mechanical-strain gauge data measuring on a package and a PCB under a 4-point bending test has been used for the finite element model's verification [6]. Strain gauges were applied to monitor the mechanical strains developed across all four corners of a lidless flip-chip ball grid array (BGA) package during a heatsink mounting process [7]. Strain gauge measurements were also carried out for the PCB assembly under thermal loading to validate the finite element simulation results [8]. Regarding full-field measurements, the optical shadow moiré system has been used for out-of-plane deformation (or warpage) measurements in a PCB assembly and electronic components [9–11]. This optical method has been effectively and successfully used to measure the full-field out-of-plane deformations of electronic packages, and the PCB under different temperatures, by studying the residual strain in the epoxy molding compound in plastic BGA packages [12,13] and the warpage of a CPU socket [14]. However, there is no out-of-plane deformation measurement available in the literature for a PCB assembly using strain gauges during a solder reflow process.

In order to monitor the warpage variation of a PCB assembly in real time under heating and cooling during a solder reflow process, especially in a conventional IR oven (although some of such preliminary results have been reported in [15,16]), a warpage measurement of a PCB with strain gauges during the reflow process will be proposed in this study. Its feasibility will be evaluated by the shadow moiré system and finite element method (FEM) analysis.

2. Methodologies

In this study, three methods, including strain gauges, full-field shadow moiré, and FEM analysis were employed for measuring and calculating the curvature and deformations (or warpages) of a PCB with surface-mount dual in-line memory module (DIMM) sockets under thermal loads. The test sample, provided by Inventec Corporation, is the PCB mounted with six surface-mount DIMM sockets (called the PCB assembly here) shown in Figure 1a, in which the bare PCB before the mounting sockets has the size of $220 \times 72 \times 2.5$ mm, as shown in Figure 1b. During the reflow heating process, the DIMM sockets and PCB expand freely and differently due to the liquid-state (or paste-state) solder material without any constraint, as shown in Figure 2a. However, during the reflow cooling process, from 250 to 30 °C (equivalent with a thermal load of -220 °C), the solder material becomes solidified and provides a constrained force between the DIMM sockets and the PCB. Therefore, the PCB and DIMM sockets would deform and warp simultaneously resulting from the CTE mismatch under a thermal load, as illustrated in Figure 2b.

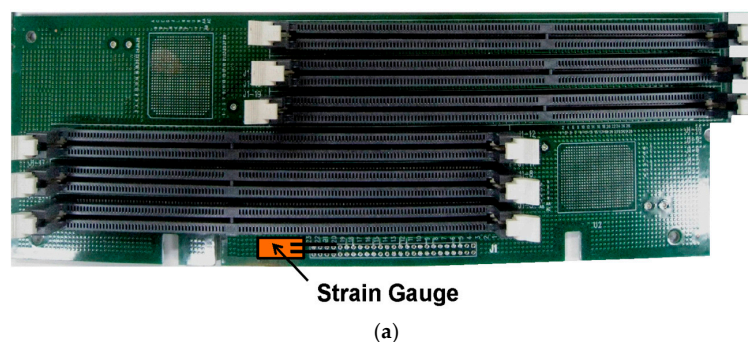


Figure 1. Cont.

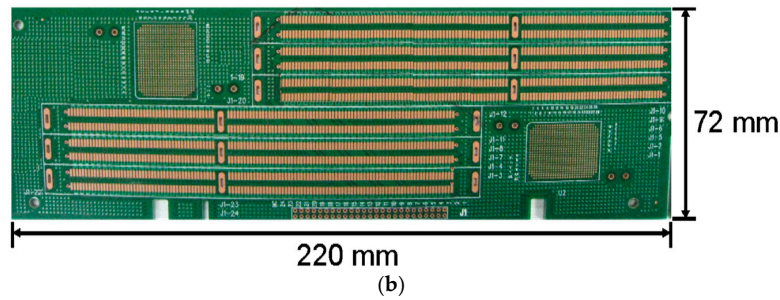


Figure 1. Configurations of (a) the printed circuit board (PCB) with dual in-line memory module (DIMM) sockets (called a PCB assembly), in which (b) the bare PCB is with the size of $220 \times 72 \times 2.5$ mm.

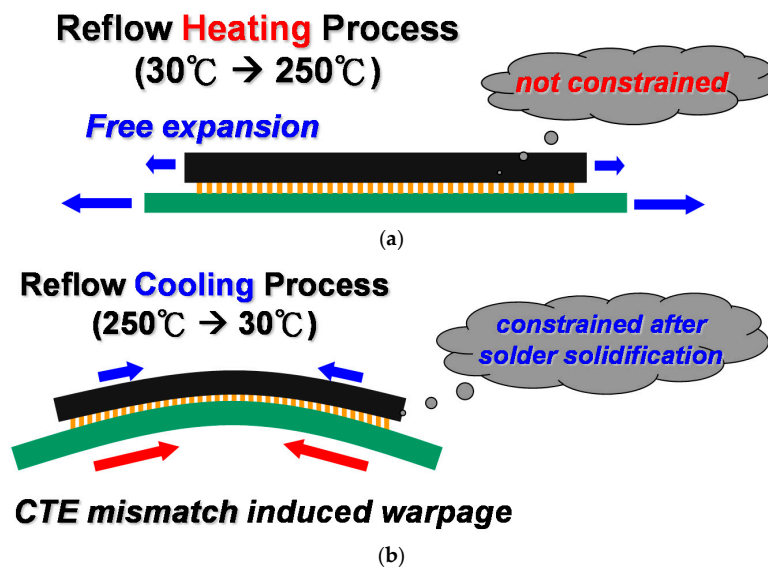


Figure 2. (a) No constraint between DIMM socket and PCB during the reflow heating process, and (b) thermally-induced warpage of the PCB assembly due to a coefficient of thermal expansion (CTE) mismatch during the reflow cooling process.

Before the reflow process, back-to-back strain gauges were adhered to a specific position on both the top and bottom surfaces of the PCB, as shown in Figure 1a, for measuring the strains on the PCB during the reflow process. The strain data with the variation of temperature were further converted into bending strains (ϵ_b) and bending curvatures (k) of the PCB by Equations (1) and (2), respectively. Then, the out-of-plane deformation of the PCB under different temperatures could be further calculated by Equation (3) for a given curvature:

$$\epsilon_b = \frac{(\epsilon_{top} - \epsilon_{bottom})}{2}; \quad (1)$$

$$k = \frac{2\epsilon_b}{h}; \quad (2)$$

$$W = \frac{kx^2}{2}. \quad (3)$$

where ϵ_{top} is the strain on the PCB surface with DIMM sockets, ϵ_{bottom} is the strain on the PCB back surface, h is the PCB thickness, and W is the maximum out-of-plane displacement (deformation) at the given distance x with constant curvature k .

For measuring the out-of-plane deformation of the PCB either before or after the reflow process, an optical full-field shadow moiré system was employed in this study. It is expected that a significant warpage change occurs on the PCB after the cooling reflow process (from 250 to 30 °C) due to the CTE mismatch. The measured deformations of the PCB assembly will further be compared with those from the strain gauge measurement and the FEM simulation.

In the FEM simulation, an isothermal linear analysis was performed to calculate the CTE mismatch-induced PCB deformation or warpage. The material properties for the PCB, DIMM socket, and solder material are listed in Table 1. Among those material properties, the effective CTEs (α) of the PCB and socket have been carefully measured using strain gauges in this study, but not for the solder material since it is relatively thin, while non-sensitive data such as the elastic modulus (E) and Poisson ratio (ν) have been taken from the literature. The schematic drawing and the FEM model are also shown in Figure 3 with the related boundary conditions and meshes. An applied thermal load of $\Delta T = -220$ °C (from 250 °C cooling down to 30 °C) is chosen as to mimic the thermal loading in the reflow cooling process. Then, the FEM simulation results will be further compared with those from the strain gauge measurement in terms of curvatures and from the moiré measurement in terms of deformations.

Table 1. Material properties of PCB, DIMM socket, and solder used in the finite element method (FEM) simulation

Material	E (GPa)	α (ppm/°C)	ν
PCB	20	18	0.28
DIMM Socket	19	11.3	0.3
Solder	49	20	0.4

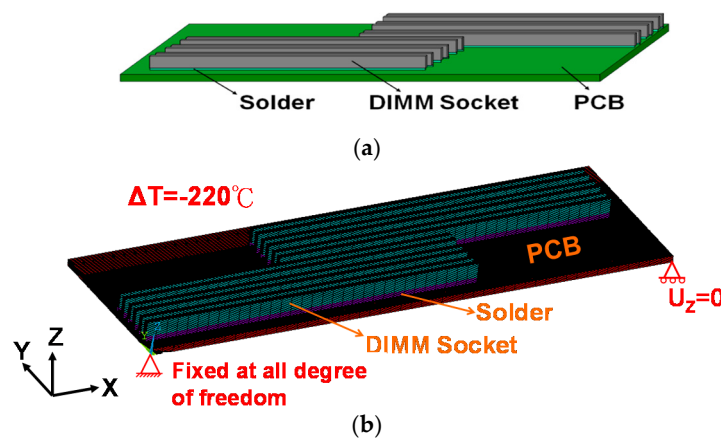


Figure 3. (a) Schematic drawing and (b) the modeling of the PCB with DIMM sockets in the finite element method (FEM) simulation.

3. Results and Discussion

3.1. Thermal and Curvature Data Verifications

For the calibration of the temperature field and gradient on the test sample during the reflow process, a Cu/core bi-material specimen (with a size of $40 \times 40 \times 0.4$ mm) instrumented with back-to-back thermocouples was heated separately in a commercial IR reflow oven and a conventional oven. It is noted that the reason for the use of the bi-material specimen is that this specimen deforms with one curvature (almost across the entire surface) at a given temperature load. The temperature profiles from the Cu and core surfaces, as shown in Figure 4, indicate that there is no temperature gradient across the thickness of the bi-material specimen for the reflow oven with a specimen moving

velocity of 0.2 m/min, but not 0.4 m/min. This temperature profile on the Cu/core bi-material specimen in an IR reflow (with a specimen moving velocity of 0.2 m/min) and in a conventional oven, as shown in Figure 5, show no temperature gradient across the thickness of the specimen in both ovens. Furthermore, this bi-material specimen with back-to-back strain gauges was heated in both ovens, and then the curvatures of the specimen, obtained from the back-to-back strain data associated with Equations (1) and (2) and the moiré data with Equation (3), are shown in Figure 6 with different temperatures. The results indicate that the curvature data from the strain gauge measurement in the IR reflow oven linearly change with the temperature, and are in a good agreement with those from both the strain gauge measurements and moiré measurements in the conventional oven. Therefore, it has been proved that a strain gauge measurement can be used for extracting the curvature data from the test specimen during the IR reflow process.

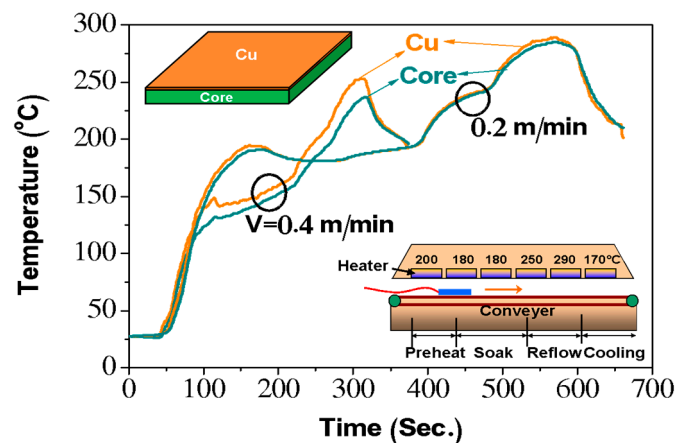


Figure 4. Temperature profiles for a Cu/core bi-material specimen with a size of $40 \times 40 \times 0.4$ mm (Cu 0.03 mm/core 0.37 mm in the thickness) in an IR reflow process with a conveyer velocity of 0.2 m/min and 0.4 m/min.

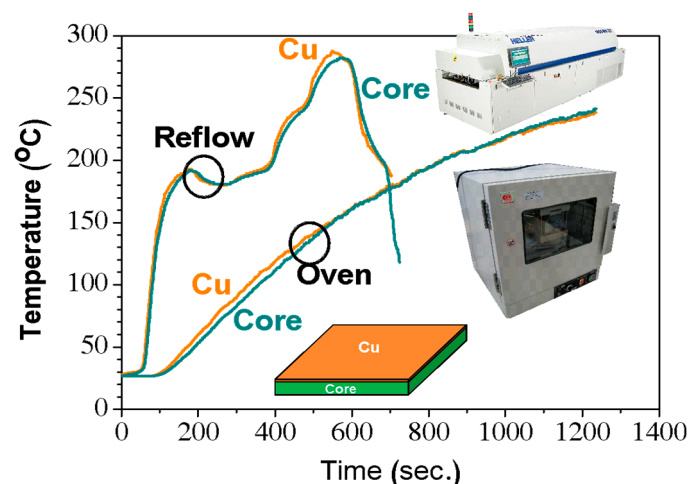


Figure 5. Temperature profiles on the Cu/core bi-material specimen in an IR reflow oven (with a specimen moving velocity of 0.2 m/min) and in a conventional oven.

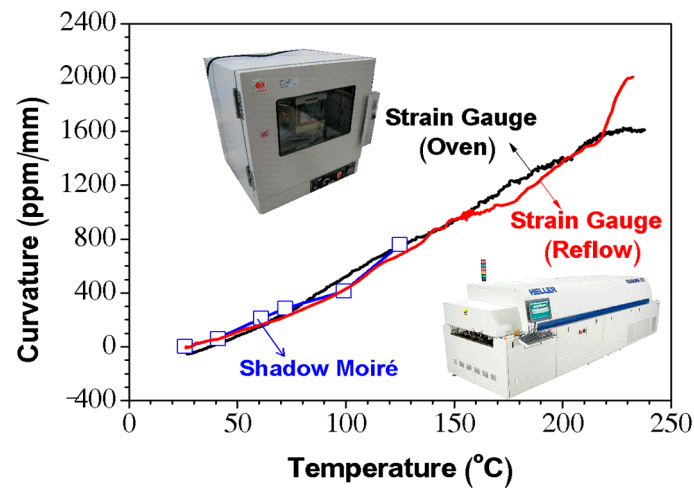


Figure 6. Experimentally obtained curvature variation of the Cu/core bi-material specimen with temperatures, obtained from strain gauges and shadow moiré in both conventional and IR reflow ovens.

3.2. Measurements of Curvatures and Deformations

For the in situ measuring of the PCB's curvature (which may not be constant across the entire surface, in contrast to the bi-material specimen) and warpage during the reflow process, back-to-back strain gauges were adhered on both the top and bottom surfaces of the PCB. The original strain data are shown in Figure 7a, which indicates that there is a slight strain difference between both surfaces during the reflow heating process. On the contrary, during the cooling process, the strain difference becomes more obvious due to the solidification of solder and the CTE mismatch between both the DIMM sockets and PCB. Then, the curvature data of the PCB was further calculated from Equations (1) and (2) and is shown in Figure 7b. It is shown that the curvature value decreases to $-50 \times 10^{-6} \text{ mm}^{-1}$ during the heating process, due to the deformation of the bare PCB. However, this value starts to build up to $207 \times 10^{-6} \text{ mm}^{-1}$ as the PCB is cooled down from 250 °C to 30 °C, resulting from the mutual constraint between the PCB and DIMM sockets after the solder's solidification.

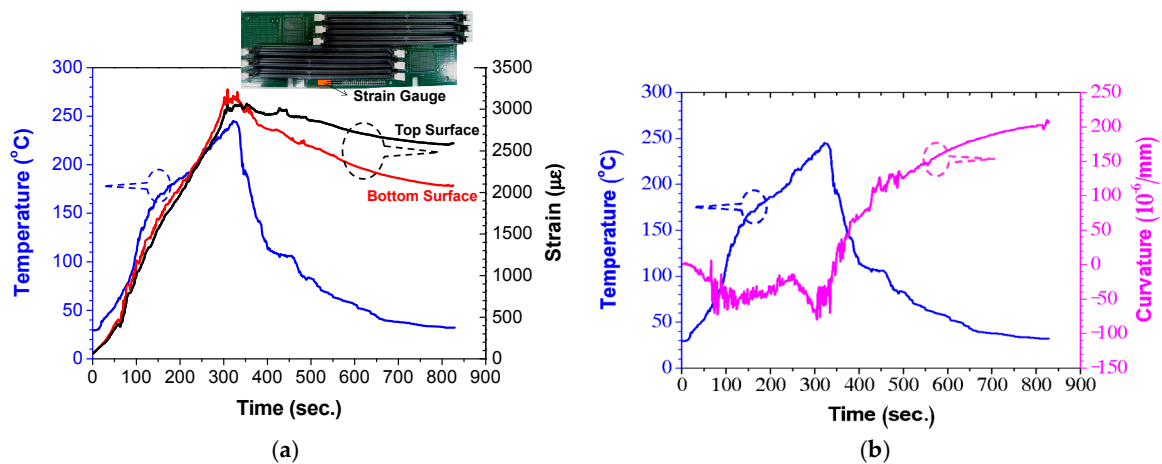


Figure 7. (a) Strain data measured by one pair of strain gauges on the top and bottom surfaces of the PCB and temperature profile during reflow process, and (b) the obtained curvature of the PCB and temperature profile with different time.

In addition, the out-of-plane deformations of the bare PCB and PCB assembly were also measured individually by a full-field shadow moiré system. Figure 8a illustrates the out-of-plane deformation results along line a–d of both PCBs before and after the reflow process. The deformation difference, shown in Figure 8b, was obtained by subtracting the deformation before re-flow from the one after re-flow and adding the shifting and rigid-body rotation. The result indicates that the warpage change of the PCB assembly after the reflow process is about 1100 μm .

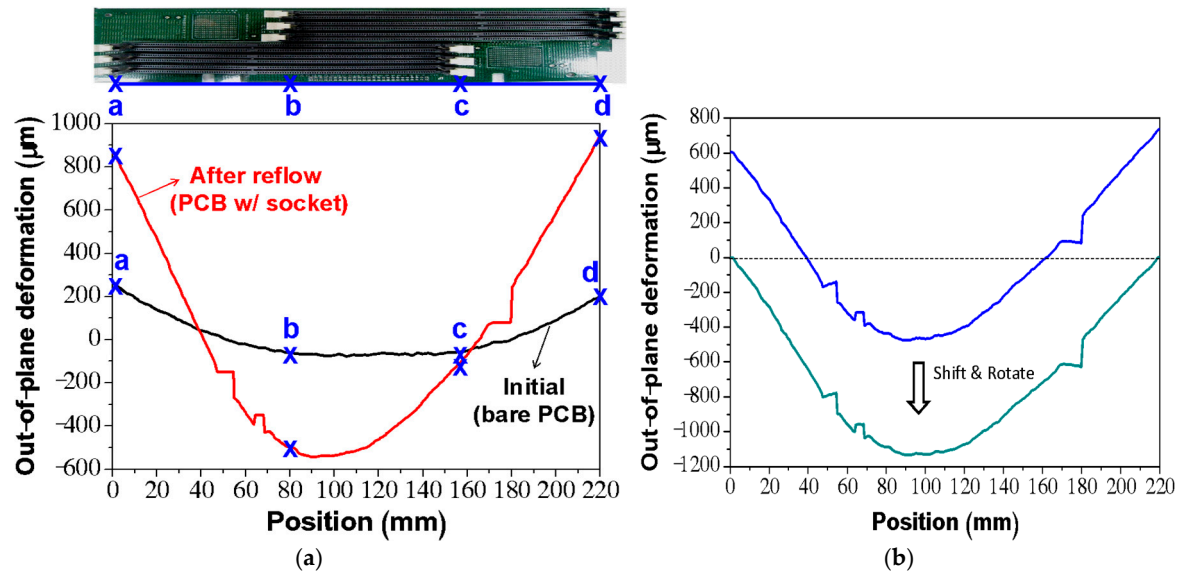


Figure 8. (a) Out-of-plane deformation of the bare PCB and PCB with DIMM sockets (after the reflow process) measured from shadow moiré, and (b) thermally-induced out-of-plane deformation of the PCB with DIMM sockets.

3.3. Deformation Validation by FEM

In the FEM simulation, a thermal load of $-220\text{ }^{\circ}\text{C}$ (from $250\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$) was applied for calculating the curvature or warpage of the PCB during the reflow cooling process. Figure 9 shows the curvature distribution along the edge line a–d on the PCB assembly from the simulation's result. Note that the valley appearing at the position of 140 mm is caused by the free end effect of the three sockets at the front. It is shown that the curvature at the same location of the strain gauge is $205 \times 10^{-6}\text{ mm}^{-1}$, which fairly equals the value of $207 \times 10^{-6}\text{ mm}^{-1}$ measured from strain gauge during the reflow cooling process. Furthermore, the full-field out-of-plane deformation in Figure 10 from the FEM simulation shows a cylindrical bending of the PCB assembly at room temperature after the solder reflow. With regard to the out-of-plane deformation of the PCB along line a–d, the out-of-plane deformation measured from shadow moiré is quite close to that from the FEM simulation, as shown in Figure 11. Hence, the FEM simulation for calculating the curvature or warpage of the PCB assembly is proved to be valid.

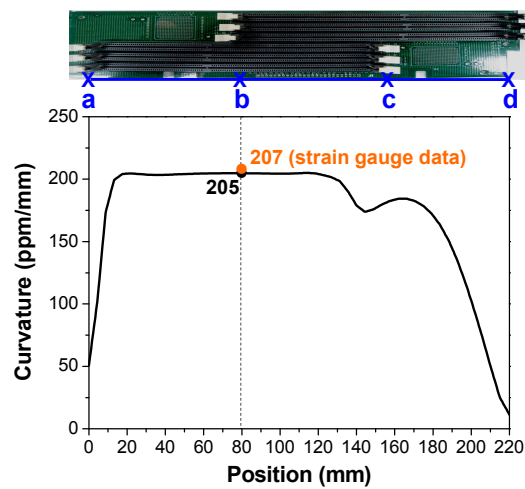


Figure 9. Curvature distributions along edge line a-d on the PCB assembly at room temperature after the solder reflow process from the FEM simulation, and one curvature data from the strain gauge measurement.

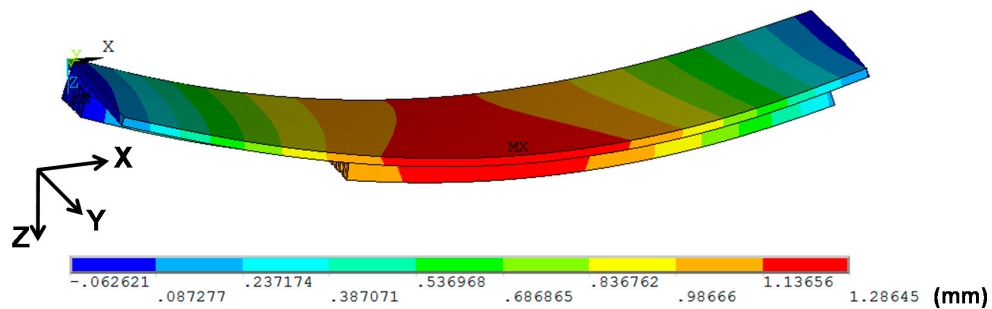


Figure 10. Full-field out-of-plane deformation (W) for the PCB assembly at room temperature after the solder reflow, obtained from the FEM simulation ($\Delta T = -220$ °C).

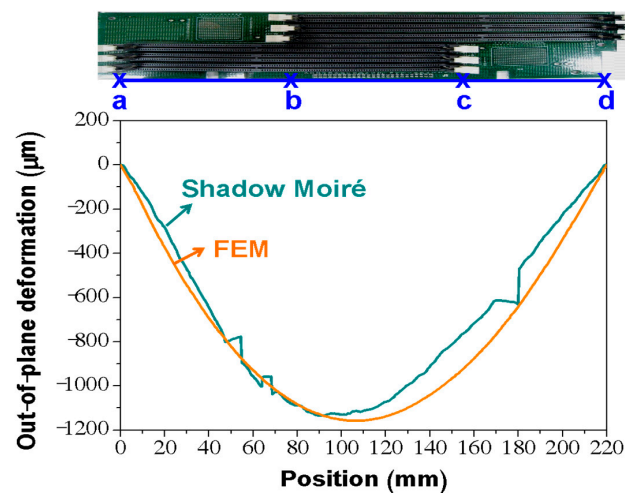


Figure 11. Comparison of out-of-plane deformation of the PCB assembly between shadow moiré experiment and FEM simulation.

3.4. Construction of Deformation and Warpage Using Gauge Data

After the proof that an FEM simulation can successfully describe the thermally-induced deformation of the PCB assembly, the discrete curvature data at different points from the FEM model representing the data obtained from the strain gauges were employed for constructing the deformation and warpage of the PCB assembly. Since the PCB's curvature may not be constant across the entire surface, a simple beam model with multiple curvatures for an out-of-plane deformation calculation is proposed and shown in Figure 12. This model is based on a beam theory with an assumption of a small deflection. The k_i is a constant curvature of a segment i between the length L_{i-1} and L_i . The associated equations of deflection W_i within the segment i are listed as follows:

$$\begin{aligned}
 x = 0 &\Rightarrow W_0 = 0 \\
 0 \leq x \leq L_1 &\Rightarrow W_1(x) = \frac{1}{2}k_1x^2 \\
 L_1 \leq x \leq L_2 &\Rightarrow W_2(x) = W_1(L_1) + k_1L_1(x - L_1) + \frac{1}{2}k_2(x - L_1)^2 \\
 L_2 \leq x \leq L_3 &\Rightarrow W_3(x) = W_2(L_2) + [k_1L_1 + k_2(L_2 - L_1)](x - L_2) + \frac{1}{2}k_3(x - L_2)^2 \\
 &\bullet \\
 &\bullet \\
 &\bullet \\
 L_{i-1} \leq x \leq L_i &\Rightarrow W_i(x) = W_{i-1}(L_{i-1}) + \sum_{m=1}^{i-1} [k_m(L_m - L_{m-1})](x - L_{i-1}) + \frac{1}{2}k_i(x - L_{i-1})^2
 \end{aligned} \tag{4}$$

The curvature data can be obtained from the strain gauges by back-to-back attaching on the PCB. To validate this proposed approach, curvature data at one, three, and six points (shown in Figure 13a obtained from the FEM simulation to represent the data from the strain gauge measurement were selected for calculating the out-of-plane deformation of the PCB assembly using this simple model. The results are shown in Figure 13b,c for out-of-plane deformations of the PCB assembly along line A–D and warpage, respectively, in comparison with the FEM result (baseline). It is shown that the more data used, the closer the deformed curve is to the baseline simulation. In addition, the warpage can reach the baseline within a 7% to 2% difference by using only one-point to six-point data. Therefore, the curvature data from the strain gauge measurement can be successfully applied to determine the out-of-plane deformation and warpage of the PCB assembly under a solder reflow process.

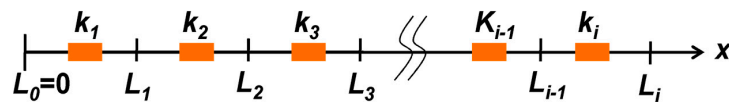


Figure 12. The simple beam model for calculating out-of-plane deformation.

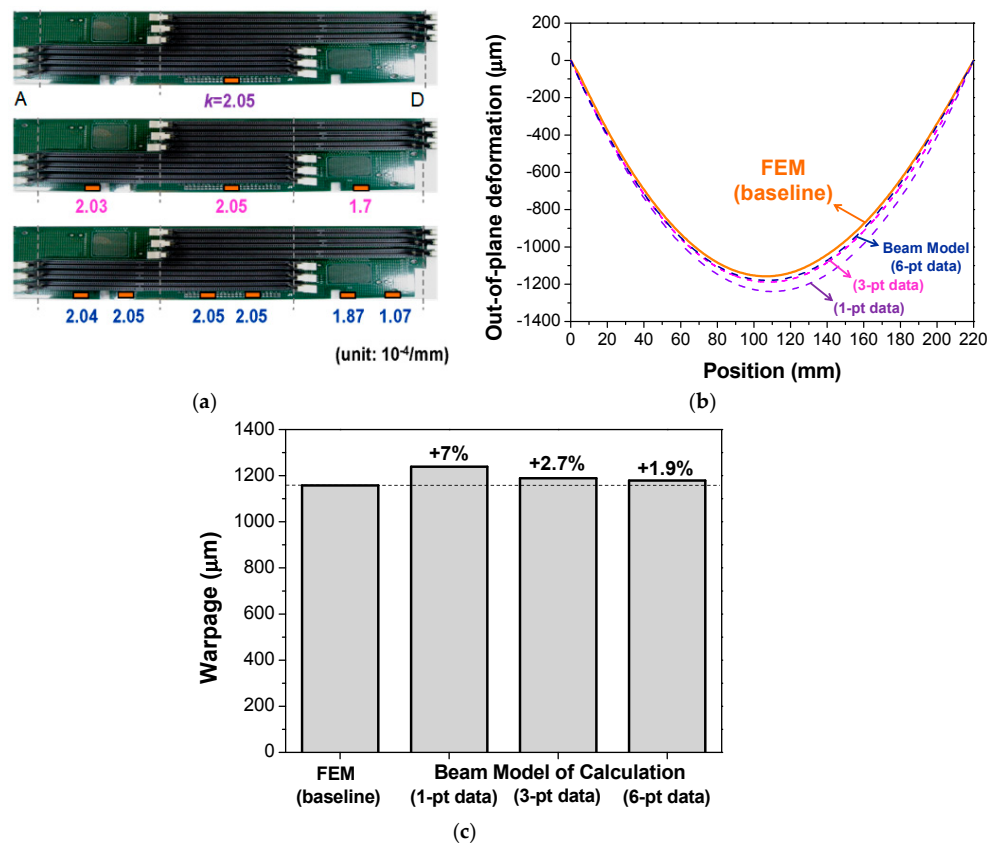


Figure 13. (a) Given curvature data (at one, three, and six points) obtained from the FEM simulation (representing data from the strain gauge measurement); (b) out-of-plane deformation of the PCB assembly along line a-d obtained from the simple beam model, compared with the FEM simulation (baseline); (c) warpages from the simple beam model of calculation with various numbers of curvature (or strain) data.

4. Conclusions

In this study, a strain gauge measurement has been proved to be feasible for determining the thermally-induced bending strains of a PCB during the solder reflow process, through the investigation of the out-of-plane deformation problem with a bi-material plate and a PCB assembly using a shadow moiré measurement and a finite element analysis. These gauge-obtained bending strains can be further converted with the specific equations into the curvature data and with a simple beam model into global deformations or warpages, which are consistent with those from the shadow moiré measurement and the finite element simulation. A simple beam model associated with multiple curvature data from the strain gauge measurement has been proposed for quantifying thermally-induced out-of-plane deformations or warpages of the PCB during the reflow process. In conclusion, this approach has been proved to be a workable and easy-to-use method for real-time monitoring of PCB deformations or warpages during the solder reflow process.

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Conflicts of Interest: The authors declare no conflict of interest.

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