Deformation of solder joint under current stressing and numerical simulation—II

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Abstract

In this paper, the Moiré interferometry technique is used to measure the in situ displacement evolution of lead-free solder joint under electric current stressing. Large amounts of deformation were observed in the solder joint under high density (above 5000 A/cm^2) current stressing. The deformation was found to be due to electromigration in the solder joint and an electromigration constitutive model was applied to simulate the deformation. Both the experimental observations and finite element method (FEM) simulation results indicate that, in addition to the current density level, the current density distribution within the solder joint has a great effect on the displacement development in the solder joint under current stressing. Specifically, greater non-uniformity in current density leads to greater normal deformations within the solder joint in this test module. This is the second part of a series of papers reporting on the deformation of solder joints under current stressing.
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1. Introduction

Electromigration in solder joints under high direct current density is a known reliability concern for future high-density microelectronic packaging and power electronics packaging (Lee et al., 2001; Lee and Tu, 2001; Ye et al., 2002a,b,c; Ye et al., 2003a,b). The trend in flip-chip and Ball Grid Array (BGA) packaging to increase I/O count drives the interconnecting solder joints to be smaller in size and therefore carry a higher density current. The current density also increases as chip voltage decreases and absolute current levels increase. Flip-chip power semiconductors and system-on-package power processors are also driven to increased current density because of a demand for smaller size joints (Liu et al., 1999, 2000; Liu and Lu, 2001; Paulasto-Krockel and Hauck, 2001). Electromigration in solder joints is a physical limit to the current density of both microelectronics and power electronics.

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In the first paper in this series, we reported on observations of deformation in the solder joint under current stressing and determined that the deformation was due to electromigration. A coupled diffusion-mechanical electromigration model was used to simulate the deformation evolution of the lead-free solder joint under current stressing. The displacement results of the simulation were reasonably close to the Moiré interferometry experimental results in both spatial distribution and time history evolution. This indicates that the electromigration model is reasonably good at predicting the mechanical behavior of lead-free solder alloys under electric current stressing. In this second paper, we gathered more Moiré interferometry experimental results along with the finite element method (FEM) simulation. Both the experimental observations and the FEM simulation indicate that, aside from the current density level, the current density distribution within the solder joint has a great effect on the displacement development within the solder joint during current stressing.

The lead-free solder alloy used to fabricate the test module in the Moiré Interferometry experiment is $Sn_{95.5}/Ag_4/Cu_{0.5}$ as described in the first paper.

2. Test sample and fixture schemes

The detailed information about test sample preparation and test fixture set-up is also available in the first part of this paper. With improved measures of sample preparation and test fixture design, we achieved high current density in the test solder joint without generating a large amount of heat.

3. Moiré interferometry experiments on lead-free solder joints

This paper includes two more sets of Moiré interferometry experimental results. The test modules are named M-Pbfree-1 and M-Pbfree-2 and the current stressing densities are 0.6×10^4 A/cm^2 and 1.33×10^4 A/cm^2 respectively.

In module M-Pbfree-1, the smaller solder joint was polished to a thin film. The height of the solder joint is 1.5 mm with an approximate width of 1.35 mm. The joint was sectioned and polished to give an average thickness of about 0.25 mm. In the experiment, 20 A of current was applied and a current density around 6000 A/cm^2 was achieved in the solder joint. The current flow direction was controlled to be from the upper copper plate downward toward the lower copper plate in the test solder joint. The temperature was kept almost constant at 26 °C, as shown in Fig. 1. There were some temperature fluctuations (within 2 °C)
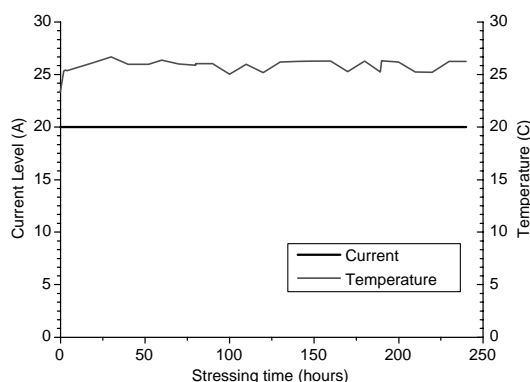

Fig. 1. Profile of applied current and measured temperature history for M-Pbfree-1.

during current stressing. This was due to ambient temperature fluctuation (the experiment lasted hundreds of hours) in the laboratory which has central air-conditioned. A thermocouple confirmed that the clamping interface did not have a higher temperature than that atop the copper plate of the test module.

The Moiré fringe evolution of module M-Pbfree-1 is shown in Fig. 2 and Fig. 3 for U and V fields, respectively. Very few U and V field fringes developed after the solder joint was stressed for 240 h. Both the U field fringes and V field fringes grew with stressing time. The U field fringes stayed nearly vertical and the V field fringes stayed nearly horizontal. This indicates that there was little shear deformation, which is in accordance with the results reported in the first part of this paper. Since the temperature was maintained nearly constant, current stressing must have caused these displacements.

For the second test module, we tried to make the stressing current density even higher in the test solder joint. We did this by applying a higher current level of 40 A. In module M-Pbfree-2, the height of the solder joint is 1.5 mm and the width is 1.2 mm. The thickness of the solder joint was polished down to 0.25 mm. In the experiment, 40 A of current was applied and a current density around 1.33×10^4 A/cm^2 was achieved in the solder joint. The current flow direction was controlled to be from the upper copper plate downward towards the lower copper plate of the test solder joint. The temperature was kept almost constant at 30 °C, as shown in Fig. 4. There were some temperature fluctuations (within 2 °C) during current stressing.
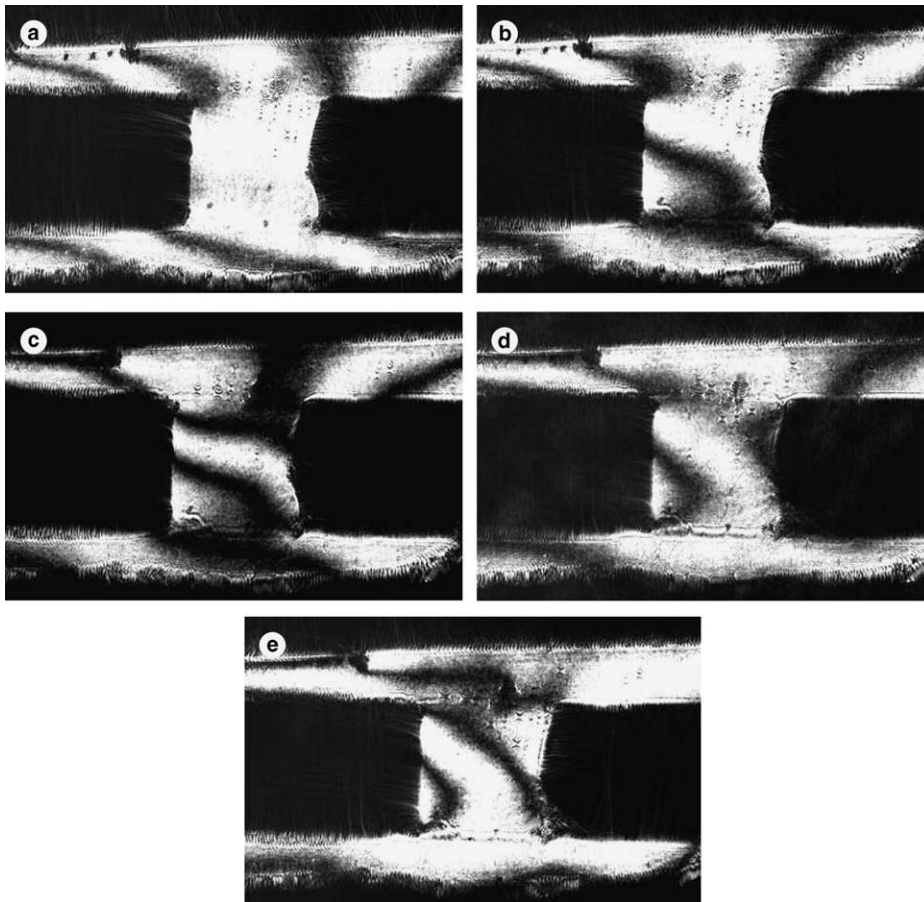

Fig. 2. U field fringe evolution: module M-Pbfree-1 (a) initial (b) 66 h (c) 115 h (d) 190 h (e) 239 h.
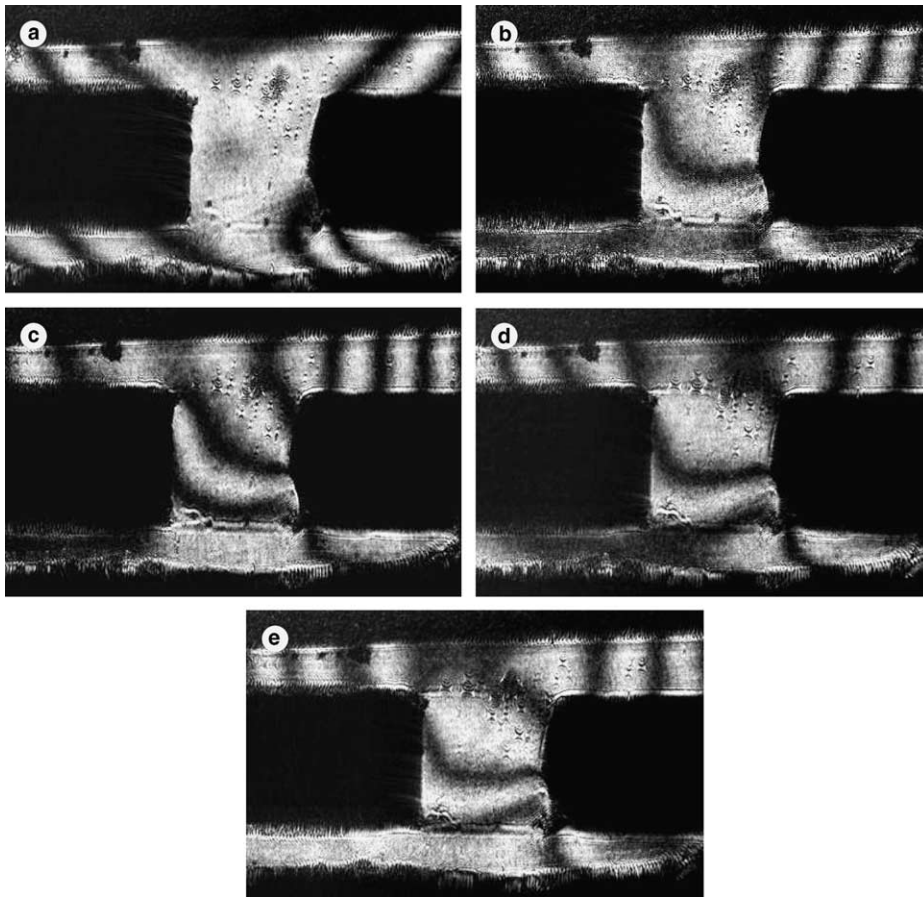
Fig. 3. *V* field fringe evolution: module M-Pbfree-1 (a) initial (b) 66 h (c) 115 h (d) 190 h (e) 239 h.
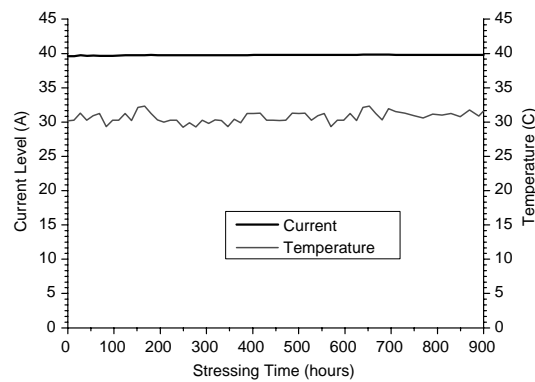

Fig. 4. Applied current and measured temperature history for M-Pbfree-2.

Thermocouple confirmed that the clamping interface did not have a higher temperature than the temperature atop the copper plate of the test module.

The Moiré fringe evolution of module M-Pbfree-2 is shown in Figs. 5 and 6 for U and V fields, respectively. Since the average current density in the solder joint of M-Pbfree-2 is higher than that in test module reported in the first part of the papers, it is reasonable to expect denser fringes in both U and V fields. However, contrary to our expectation, far fewer fringes were observed in both fields after same numbers of hours of current stressing. Both the U field fringes and the V field fringes grew with stressing time. The U field fringes stayed nearly vertical and the V field fringes stayed nearly horizontal. This
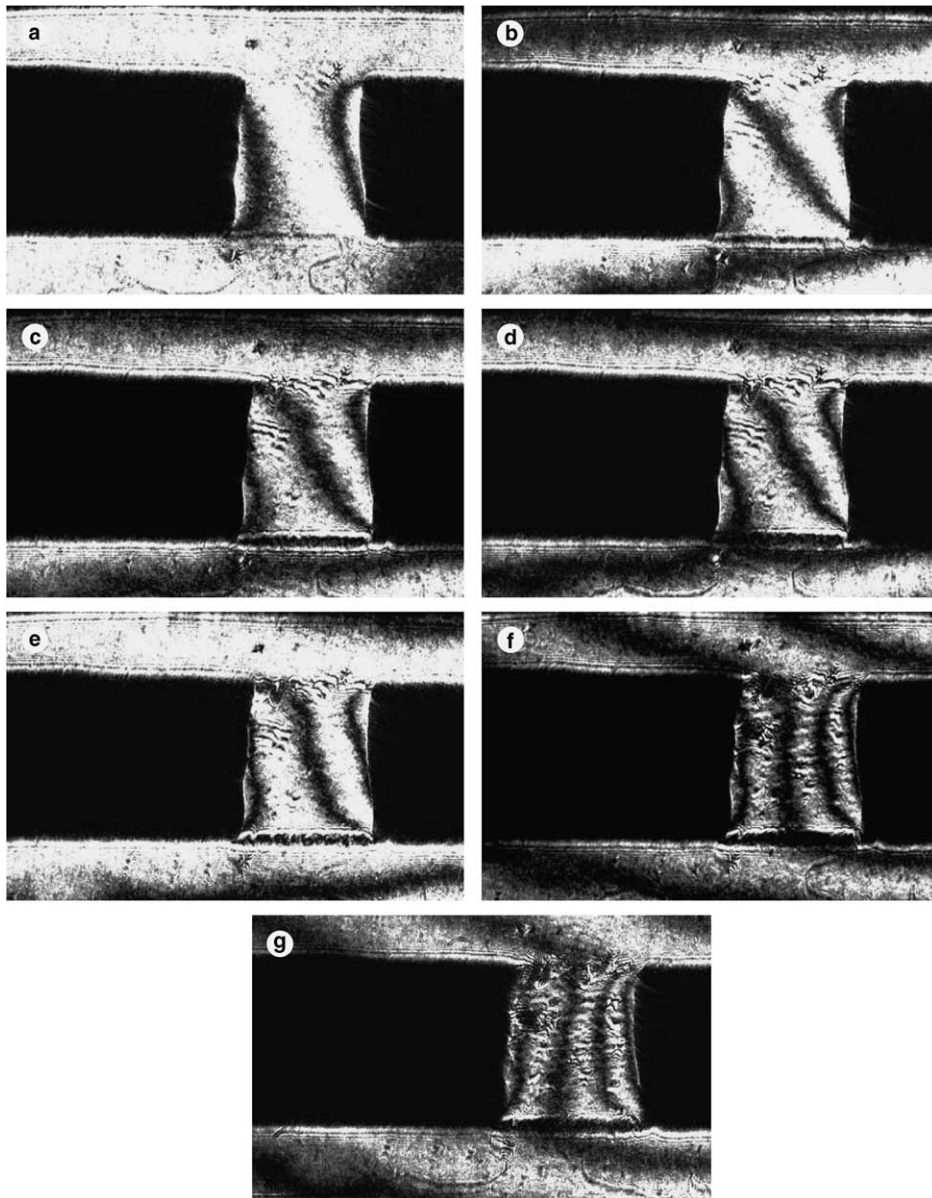

Fig. 5. U field fringe evolution: module M-Pbfree-2 (a) initial (b) 75 h (c) 263 h (d) 380 h (e) 500 h (f) 690 h (g) 879 h.
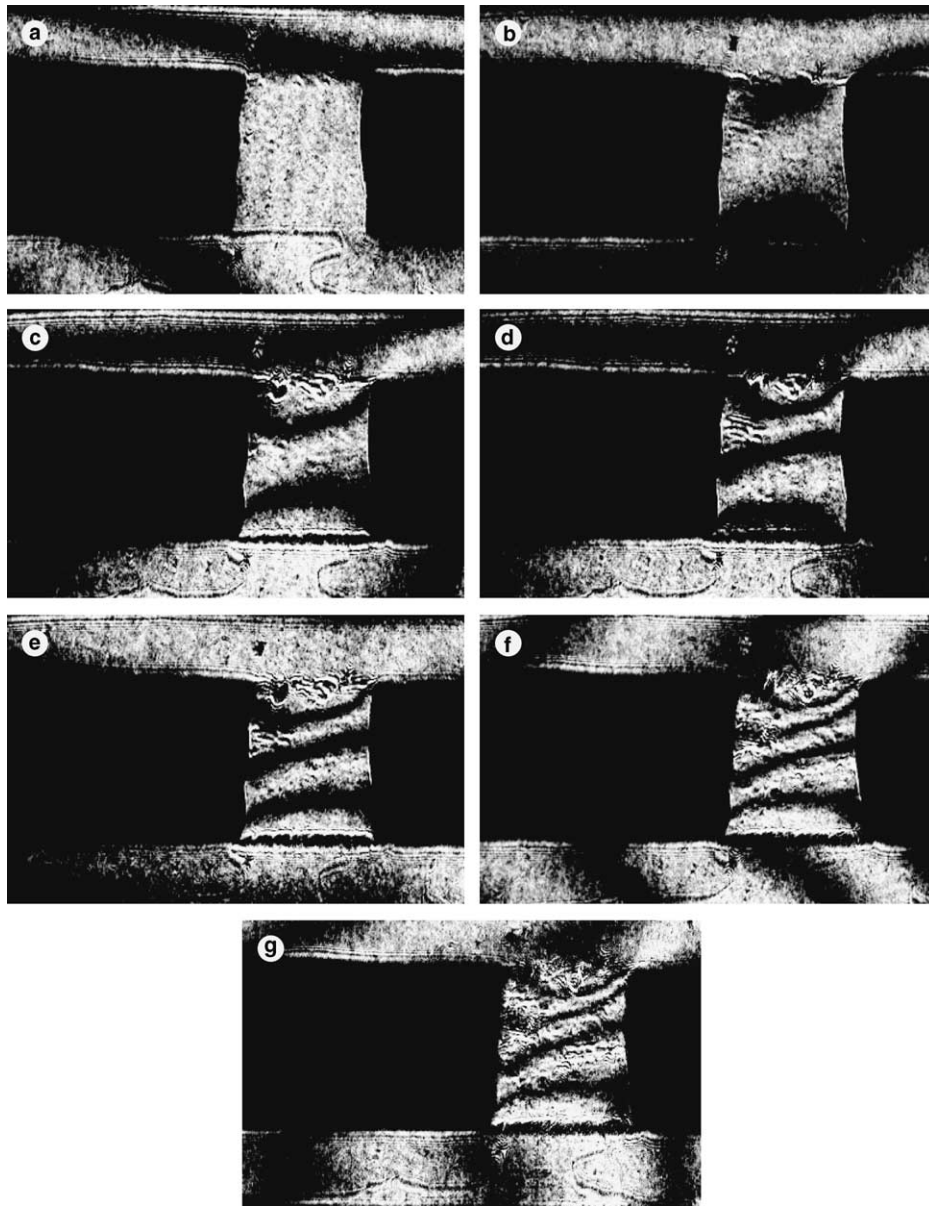
Fig. 6. *V* field fringe evolution: module M-Pbfree-2 (a) initial (b) 75 h (c) 263 h (d) 380 h (e) 500 h (f) 690 h (g) 879 h.

tendency, which is the same as in the previous experiments, confirms that electric stressing leads to normal deformation in both the horizontal and vertical directions. It is clear that in M-Pbfree-2, shear or thermal deformation was not dominant. The observation of fewer than expected fringes in this solder joint indicates that current density is not the only factor affect the fringe development. The evolutions of fringes in both fields were observed to be steady after 700 h of current stressing. This indicates that the deformation of the solder joint under electric current stressing enters steady state after 700 h of stressing.

4. Experiment results summary

Moiré Interferometry experiments on two lead-free (SnAg$_4$Cu$_{0.5}$) solder joints under high electric current density stressing were reported. During electric current stressing, the stressing temperature on the test module was well controlled and held almost constant during the course of current stressing. The current densities applied in these solder joints ranged from 0.6 to 1.33×10^4 A/cm^2. Since the temperature was held nearly constant, the deformation fringes observed during current stressing can only be attributed to current stressing. We found that high current density stressing primarily induced normal deformations within the solder joints in the test modules. This is consistent with the results reported in the first part of our paper. The deformations induced by current stressing take hundreds of hours to reach steady state, which is consistent with the fact that electromigration took hundreds of hours to reach steady state.

In both modules, fewer deformation fringes were observed in this experiment than in the test modules used in the first part of the paper. This is despite the fact that module M-Pbfree-2 was subjected to a higher current density than that in the first part of the paper (1.33×10^4 versus 1.12×10^4 A/cm^2). This indicates that current density is not the only factor that affects the deformation development within the solder joint in the test modules.

5. Numerical simulation of deformation of solder joint under current stressing

The electromigration model employed in the numerical simulation was presented in the first part of the paper. In the following simulations, exactly the same electromigration model, material parameters, boundary conditions, simulation assumptions, simplifications, and finite element codes are used as was reported in the first part of the paper. The following figures show length in cm, stress in N/cm^2 and time in seconds unless otherwise noted.

The average stressing current density in the solder joint of M-Pbfree-2 is 1.33×10^4 A/cm^2 which is higher than that in the module reported in the first part of the papers (1.12×10^4 A/cm^2). But, contrary to our expectation, there were fewer Moiré fringes observed in both the U and V fields. This shows that the current density is not the only factor determining the fringe and displacement development in the solder joint during current stressing. In the following simulations, current density distribution is found to be another important factor that affects the displacement development of the solder joint during current stressing.

The width of the solder joint in M-Pbfree-2 is 1.2 mm and the height is 1.5 mm. The average thickness of the solder joint is 0.25 mm and it is a little bit thicker near the interface between the upper copper plate and solder joint. As in the simulation reported in the first part of the paper, the variation of thickness is taken into account in the simulation. The thickness of the solder joint is assumed to be described by the following function (Fig. 7):

$$W_{\text{thickness}} = 0.025 \times (1 + 0.15 * y/0.15) \tag{1}$$

where W is the thickness of solder joint and y is the position along the height of the solder joint. The units here are in cm. This variation is implemented in the simulation by applying a non-uniform stressing current density:

$$j = 1.33 \times 10^4/(1 + 0.15 \times y/0.15) \ (\text{A/cm}^2) \tag{2}$$

where j is current density.

Figs. 8 and 9 show the simulated distributions of horizontal and vertical displacement within the solder joint along the side of the Moiré interferometry measurement after 700 h of current stressing. The simulation results of both horizontal and vertical displacements resemble the measured displacement distributions from the experiments. The value of the maximum relative horizontal displacement between the two
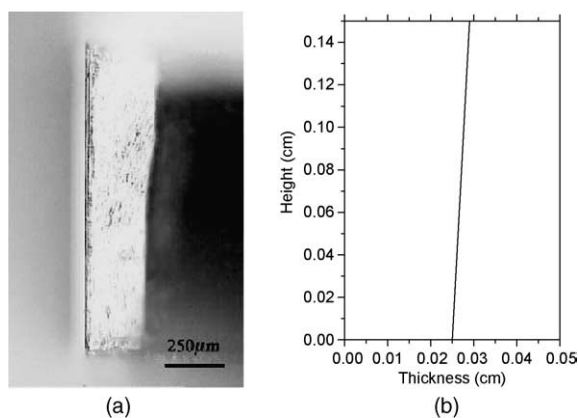
Fig. 7. Thickness of solder joint of M-Pbfree-2: (a) optical microscopic image and (b) thickness variation along the height of the solder joint used in the simulation.
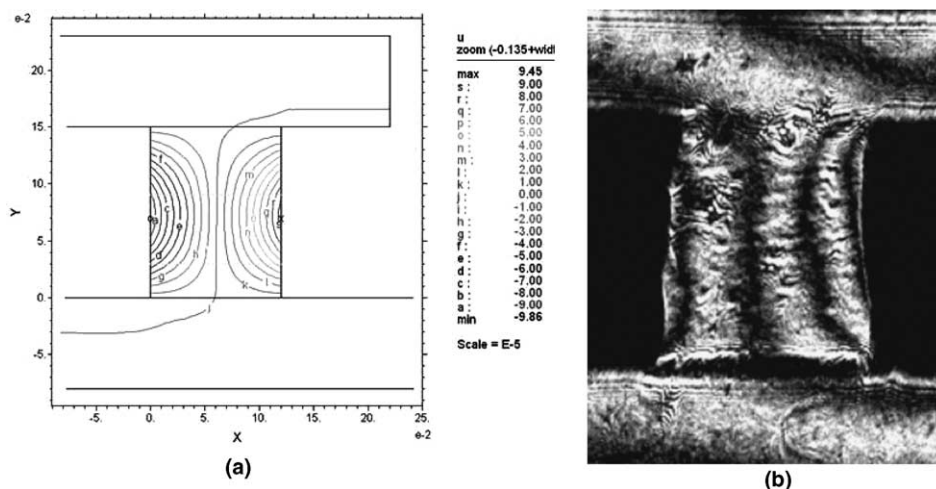

Fig. 8. (a) Simulated horizontal displacement after 700 h of current stressing in M-Pbfree-2. (b) U filed fringe development after 690 h of current stressing.

edges of the solder joint as predicted by the FEM simulation is 1.928 μm, while the experimental measurements found it to be 1.46 μm. The value of the relative vertical displacement between the upper and lower copper–solder interfaces predicted by the simulation is 1.476 μm, while the experimental displacement was found to be 1.668 μm. The results from the simulation are close to experimental observations. The exaggerated deformation of the test module after 700 h of current stressing from the simulation is shown in Fig. 10.

Fig. 11 shows a comparison of the time history evolution of relative vertical displacement between the upper and lower copper–solder interfaces. Fig. 12 shows the time history evolution of maximum relative horizontal displacement between the two edges of the solder joint. Both the simulation results and the experimental observations show that the developments of these displacements approach steady state after 900 h of current stressing. The time history evolution curves of the experimental observation do not look
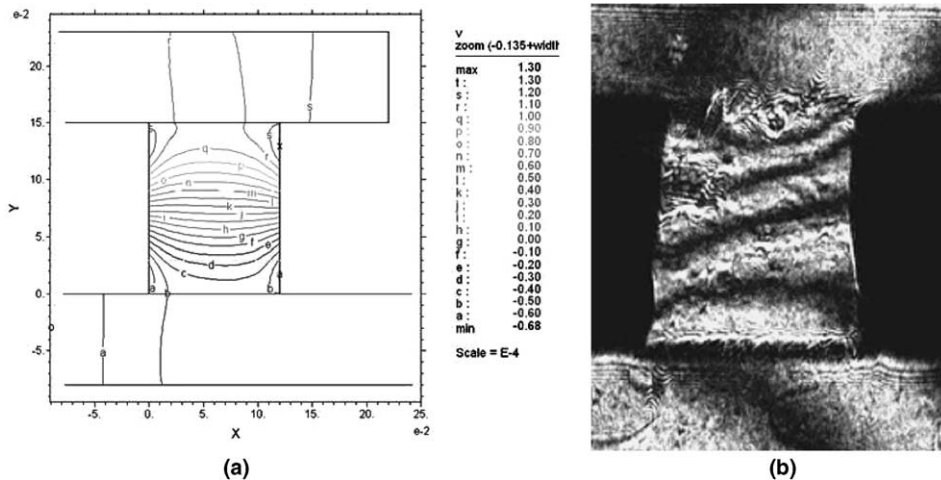
Fig. 9. (a) Simulated vertical displacement after 700 h of current stressing in M-Pbfree-2. (b) *V* filed fringe development after 690 h of current stressing.
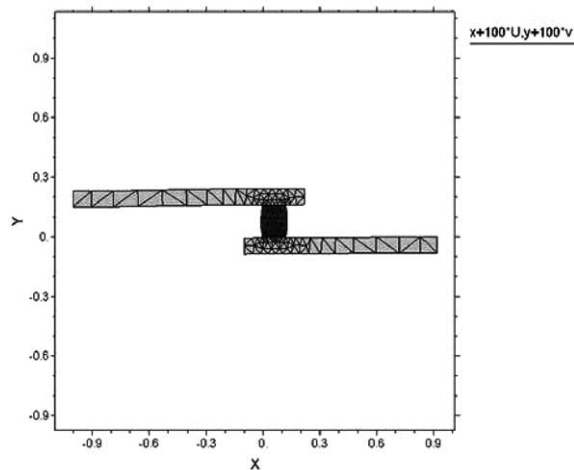

Fig. 10. Simulated deformation of M-Pbfreee-2 after 700 h of current stressing.

very smooth. This is because of the displacement resolution of the Moiré interferometry technique. With a frequency of diffraction grating at 1200 lines/mm, the displacement resolution is 0.417 μm per fringe order. The change in displacement cannot be measured accurately if it is less than 0.417 μm. As shown in these two figures, the simulation results are close to experimental observations.

As mentioned in the beginning of this section, the observed Moiré fringes in both the *U* and *V* fields in M-Pbfree-2 are fewer than those observed in the module reported in the first part of this paper despite the fact that the current density in M-Pbfree-2 is higher. The biggest difference between these two modules is the thickness variation in the solder joint. The solder joint of the module in the first part of the paper has much dramatic thickness variation than that of M-Pbfree-2. In the simulations, the thickness variation is taken into consideration by considering the current density variation within the solder joint. The current density variation within the solder joint in the simulation of the module
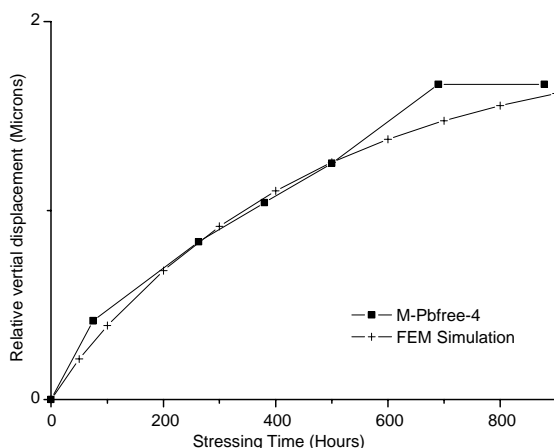
Fig. 11. Evolution of relative vertical displacement between lower and upper interface of solder joint and copper plates in M-Pbfree-2.
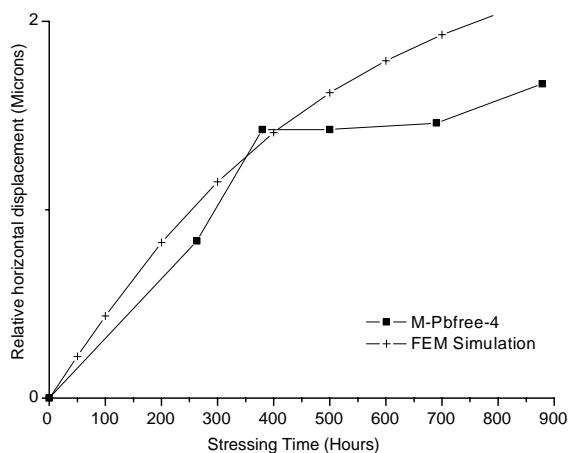

Fig. 12. Evolution of maximum relative horizontal displacement between two edges of the solder joint and copper plates in M-Pbfree-2.

reported in the first part of the paper was much greater than that in the M-Pbfree-2. The simulation results confirm that larger current density variation leads to larger displacements in the solder joint. For example, after 700 h of current stressing, the simulations predicted that the maximum relative horizontal displacement between the two edges of solder joint was 8.45 μm for the module reported in the first part of the paper compared to 1.928 μm for M-Pbfree-2, despite the fact that the maximum current density used in the simulation of M-Pbfree-2 was higher. In the first part of this paper, the simulation predicted a relative vertical displacement in the copper–solder interface after 700 h of 6.4 μm. In M-Pbfree-2 it is 1.476 μm. Therefore, both the experimental observations and the FEM simulation indicate that current density is not the only factor affecting the deformation of the solder joints and that the distribution within the solder joint has a great effect on the displacement development within the solder joint under current stressing. Specifically, greater non-uniformity among current density leads to greater normal deformations within the solder joint.
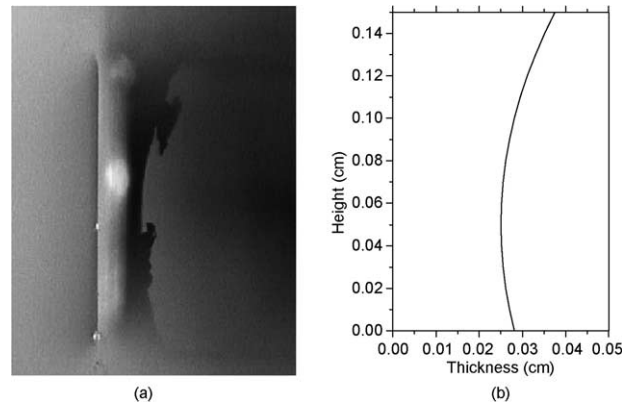
Fig. 13. Thickness of solder joint of M-Pbfree-1: (a) optical microscopic image and (b) thickness variation along the height of the solder joint used in the simulation.

The width of the solder joint in M-Pbfree-1 is 1.35 mm and the height is 1.5 mm. The average thickness of the solder joint is 0.25 mm and it is a little bit thicker near both interfaces between the copper plates and solder joint. As in the previous simulations, the variation of thickness was taken into account in the simulation.

The thickness of solder joint is assumed to be described by the following function (Fig. 13):

$$W_{\text{thickness}} = 0.025 \times \left(1 + 0.5 \times \left(\frac{y - 0.1}{0.1} \right)^2 \right) \tag{3}$$

where W is the thickness of solder joint and y is the position along the height of the solder joint. The units here are in cm. This variation is implemented in the simulation by applying a non-uniform stressing current density as follows:
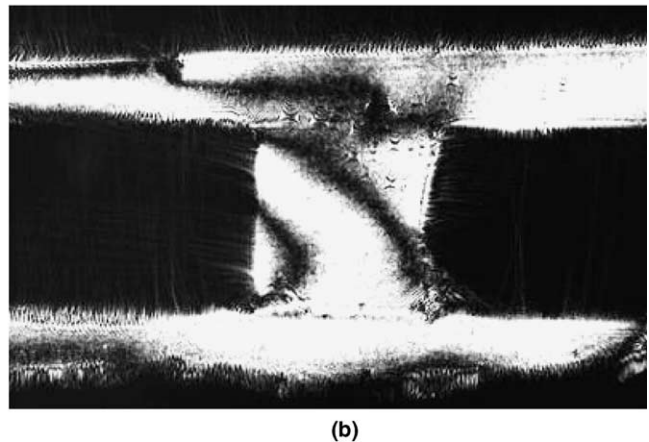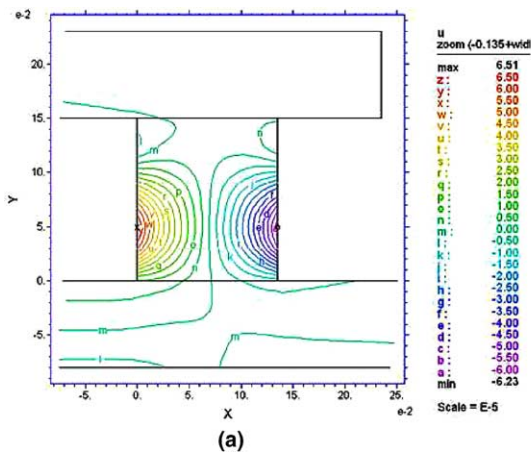

Fig. 14. (a) Simulated horizontal displacement after 200 h of current stressing in M-Pbfree-1. (b) U filed fringe development after 239 h of current stressing.
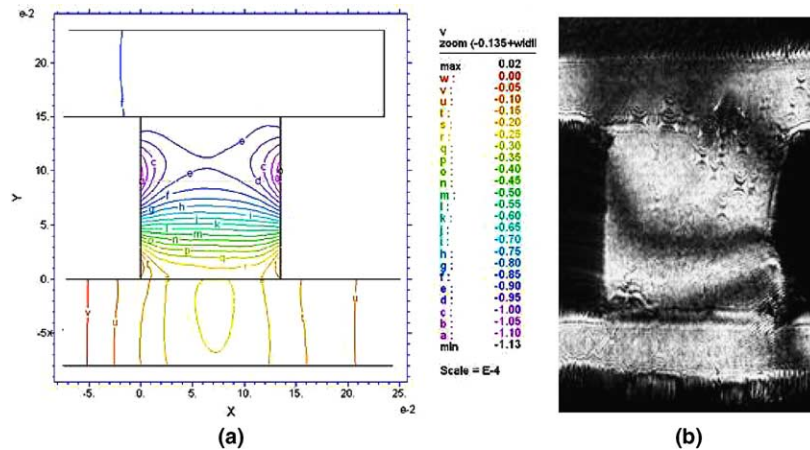
Fig. 15. (a) Simulated vertical displacement after 200 h of current stressing in M-Pbfree-1. (b) V filed fringe development after 239 h of current stressing.

$$j = 0.6 \times 10^4 \left/ \left(1 + 0.5 \times \left(\frac{y - 0.1}{0.1} \right)^2 \right) \right. (A/cm^2) \tag{4}$$

where j is current density.

Fig. 14 and 15 show the simulated distributions of the horizontal and vertical displacement within the solder joint along the side of the Moiré interferometry measurement after 200 h of current stressing. The simulation results of both the horizontal and vertical displacements resemble the experimentally measured displacement distributions. The value of the maximum relative horizontal displacement between the two edges of the solder joint predicted by the FEM simulation is 0.62 μm, while the experimental measurement found it to be 0.834 μm. The value of relative vertical displacement between the upper and lower copper–solder interfaces as predicted by the simulation is 0.898 μm, while the experimental observation showed it to be 0.834 μm. The results from simulation are close to experimental observations.
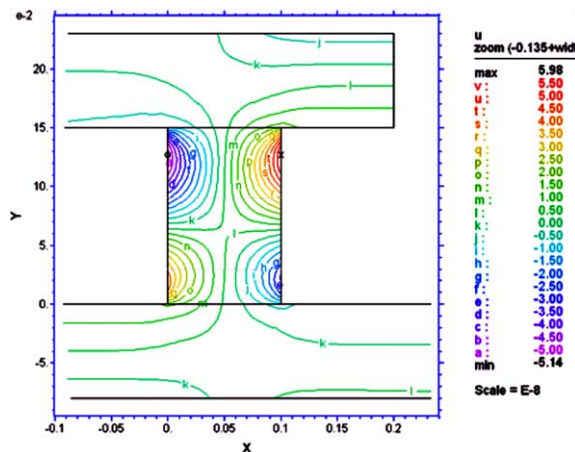

Fig. 16. Simulated horizontal displacement field after 1000 h of current stressing for uniformly distributed current density.

6. Simulation results of module with ideally uniform distributed current density

In the previous simulations, the thicknesses of the solder joints were assumed to be non-uniform due to the non-uniform thickness of the test module. In this section, a numerical simulation of a test module with a uniform solder thickness is reported. It turns out that if the thickness of an ideal solder joint is uniform, the deformation within the solder joint would be much smaller than that in a solder joint with a non-uniform thickness. In the simulation, the width of the solder joint was assumed to be 1 mm and the height was assumed to be 1.5 mm. The current density within the solder joint was assumed to be uniformly distributed at 1.2×10^4 A/cm^2 Fig. 16 and 17 show the simulated horizontal and vertical displacements fields after 1000 h of current stressing. The maximum displacement within the solder joint under uniform current density stressing is on the order of 10^{-4} μm, which is an order of magnitude smaller than those for the non-uniform current density cases under the same magnitude of current density (10^4 A/cm^2) stressing.
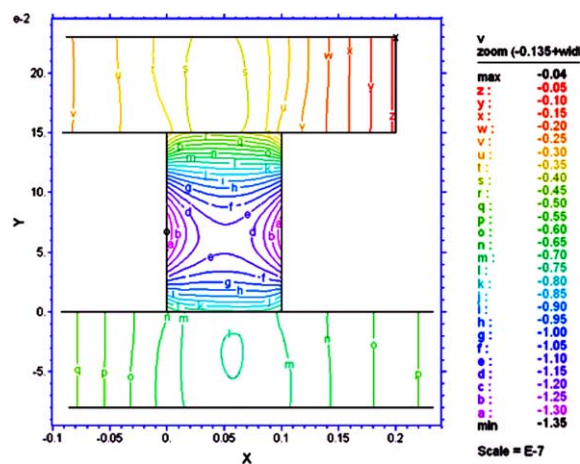

Fig. 17. Simulated vertical displacement field after 1000 h of current stressing for uniformly distributed current density.
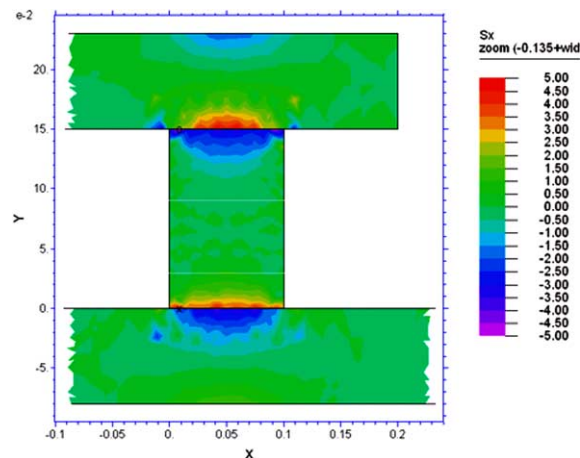

Fig. 18. Simulated normal stress σ_x distribution after 1000 h of current stressing for uniformly distributed current density.
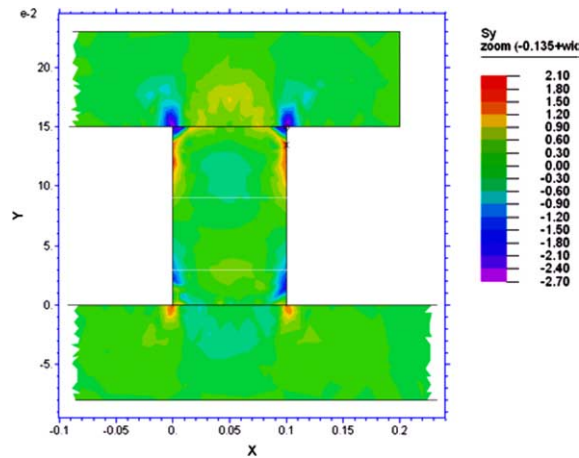
Fig. 19. Simulated normal stress σ_y distribution after 1000 h of current stressing for uniformly distributed current density.
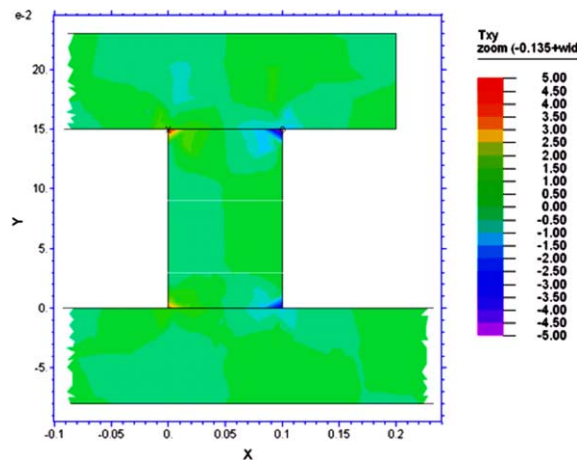

Fig. 20. Simulated shear stress τ_{xy} distribution after 1000 h of current stressing for uniformly distributed current density.

Figs. 18–20 show the simulated stress distributions within the solder joint after 1000 h of current stressing. It is clear that the stress build-up within the solder joint under uniform current density stressing is very small (on the order of 10^{-2} MPa) compared to the cases of non-uniform current density stressing (on the order of 100 MPa).

7. Conclusions

In this paper, Moiré interferometry technique was used to measure the in situ displacement evolution of lead-free solder joints under electric current stressing. Large amounts of deformation were observed in solder joint under high density (above 5000 A/cm^2) current stressing. The deformation was found to be due to electromigration in the solder joint. An electromigration constitutive model was applied to simulate the

deformation of the lead-free solder joint under current stressing. Despite all of the assumptions and simplifications employed, the simulation predicted displacement results reasonably close to the Moiré interferometry experimental results in both spatial distribution and time history evolution. This indicates that the electromigration model employed in this simulation is reasonably good at predicting the mechanical behavior of lead-free solder alloy under electric current stressing. Both the experimental observations and the FEM simulation indicate that, in addition to the current density level, current density distribution within the solder joint has a great effect on the displacement development in the solder joint under current stressing. Specifically, greater non-uniformity in current density leads to greater normal deformations within the solder joint.

Acknowledgements

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