CHAPTER IV

Effect of Substrate Flexibility on Solder Joint Reliability

4.1 Introduction

Flex substrate is very popular in electronics industry. Flex circuit packaging, a well-established technology that has been traditionally applied in IC packaging, automotive and medical electronics applications with considerable success in reducing costs, minimizing package volume, saving space for whole system, improving packaging density and maintaining electrical performance. Figure 4.1 shows some examples of flexible circuits. There are several flexible substrate manufacturers, including DuPont, 3M, Sheldahl, Minco Products Inc., and Rogers Corporation. The excellent performance of flex substrate, especially under hostile operating conditions, and the features of high insulation, low weight, high density and more importantly the flexibility make flex attractive in power electronics packaging applications.

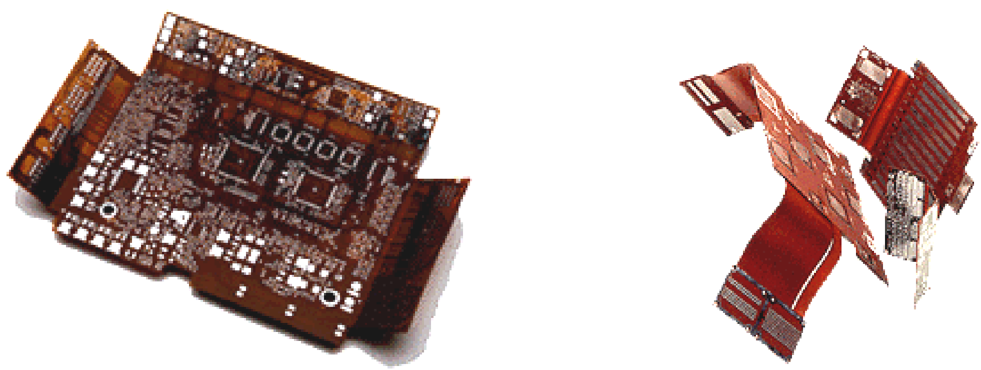


Figure 4.1. Demonstration of flexible circuits (courtesy of DuPont).

Basically, flex substrate consists of a metal layer such as Cu and a polyimide layer. The metal layer could be electroplated or laminated. In the latter case, sometime, an adhesive layer is used between the metal and polyimide layer to enhance the adhesion between the metal and polyimide. The flex substrate could be one-sided or double-sided. In order to protect the copper layer from oxidation, Ni and/or Au could be electroplated as the final surface finish. The flex substrate used in this research is double-sided, copper-clad laminate, which is an adhesiveless composite of polyimide film bonded to copper foil. This copper-clad is commercially available. This laminate has excellent handling characteristics for fabrication, outstanding dimensional stability, excellent assembly performance over a wide range of processing temperatures, low thermal expansion coefficient, excellent thermal resistance for high-temperature assembly processes and is compatible with conventional oxide treatments and wet chemical plated-through-hole desmear processes. The thickness of both the polyimide film and copper foil is 2 mil. The pattern of Cu traces is formed by photolithography and chemical etching. After processing, the substrate retains very good bend and crease flexibility.

This chapter is to investigate the effect of flex substrate on solder joint reliability. First the influence of flex substrate (flip chip on flex) on solder joint reliability is summarized. Only the important experimental results are presented since the reliability testing procedure of flip chip on flex is the same as that of flip chip on PCB in chapter 3. This chapter is focused on the study of the mechanism of substrate flexibility on solder joint reliability. Finally, experimental results are discussed.

4.2 The Influence of Flex Substrate on Solder Joint Reliability

Temperature cycling test was conducted on flip chip on flex assembly to evaluate the influence of flex substrate on solder joint reliability. Test samples were the same as those flip chip on rigid PCB substrate assemblies described in Chapter 3 except that the rigid PCB substrate was changed into flex substrate. Two test conditions were used. One is the same as the first set of temperature cycling samples and the other one is the same as the second set of samples introduced in Chapter 3. Again, electrical resistance of the solder joint interconnections was measured during the temperature cycling to serve as the failure criterion and also scanning acoustic microscopy imaging was used to detect cracks. Figure 4.2 is a comparison of the average fatigue life of flip chip on PCB board (FCOB) and flip chip on flex (FCOF) assemblies with single bump barrel-shaped solder joints and stacked hourglass/column-shaped solder joints under the first temperature cycling condition, while Figure 4.3 is a comparison of the average fatigue life of flip chip on PCB board and flip chip on flex assemblies with single bump barrel-shaped solder joints under the second thermal cycling condition. We can see from Figure 4.2 and Figure 4.3 that flex substrate improves solder joint reliability for both single bump barrel-shaped solder joint and stacked hourglass/column-shaped solder joint cases. Also it seems that relatively the thermal fatigue lifetime of single bump barrel-shaped solder joint is improved more effectively by using flex substrate than that of stacked hourglass/column-shaped solder joint.

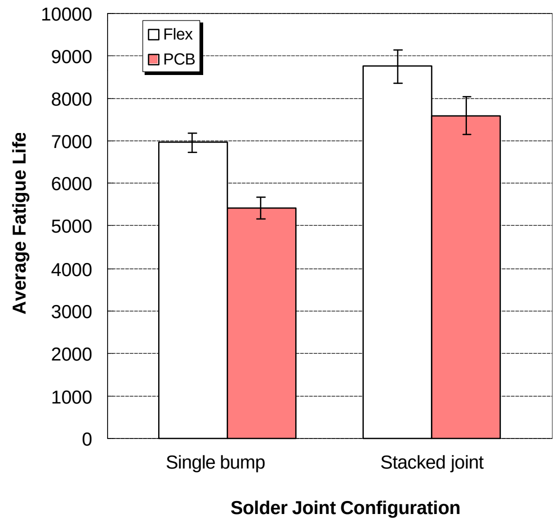


Figure 4.2. A comparison of the average fatigue life of flip chip on PCB board and flip chip on flex assemblies with single bump barrel-shaped solder joints and stacked hourglass/column-shaped solder joints under the first thermal cycling condition.

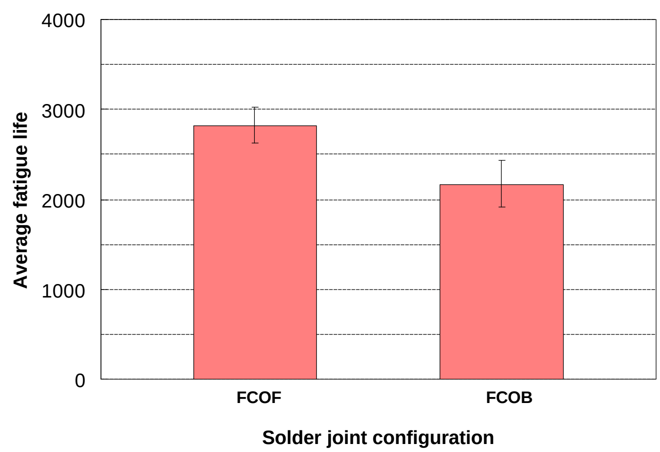
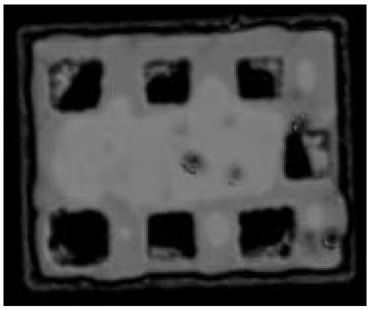
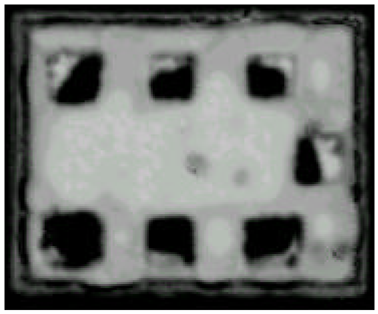


Figure 4.3. A comparison of the average fatigue life of flip chip on PCB board and flip chip on flex assemblies with single bump barrel-shaped solder joints under the second thermal cycling condition.

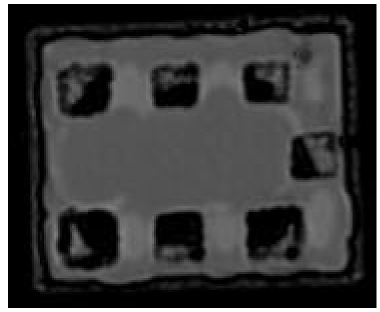
Figure 4.4 shows typical C-SAM images of the interface between single barrel-shaped solder joints and chip of a typical flip chip on flex assembly after 1400, 2000, 2400, 2800 and 3000 temperature cycles, respectively, under the second temperature cycling condition. The C-SAM images show that some parts of the solder joints had faded or were not present at all after 1400 temperature cycles. More and more areas became faded or were disappeared afterwards. As we introduced in chapter 3, crack area can be set to different colors and calculated using the National Instruments IMAQ Vision Builder software. We calculated solder joint crack area at different temperature cycles and monitored the crack growth process. Figure 4.5 shows the fractional crack area of solder joint and chip pad interface for the seven solder joints on a test chip at 1400, 2000, 2400, 2800 and 3000 temperature cycles. We can see that the fractional crack area increases with the increasing of temperature cycles.



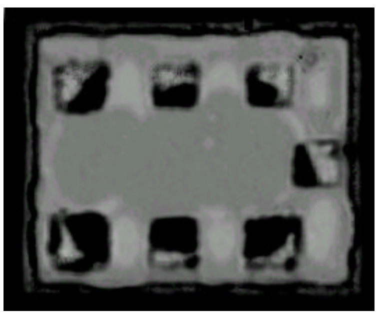
1400 cycles



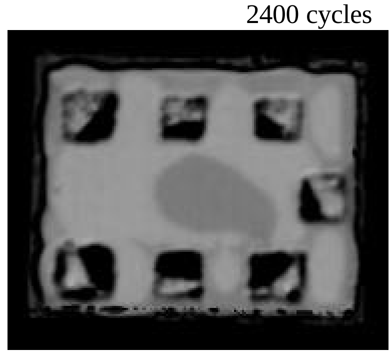
2000 cycles



2400 cycles



2800 cycles



3000 cycles

Figure 4.4. C-SAM images of the interface between single barrel-shaped solder joints and chip of a typical FCOF assembly during temperature cycling.

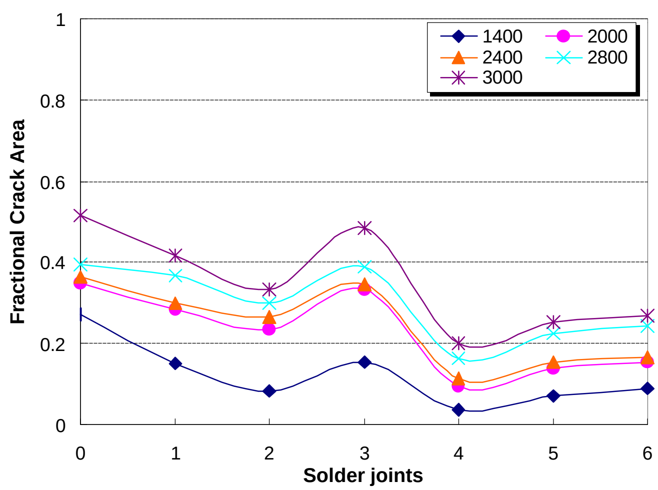


Figure 4.5. The fractional crack area of solder joint and chip pad interface for the seven solder joints on the FCOF assembly at different temperature cycles.

Figure 4.6 shows typical C-SAM images of the interface between stacked hourglass/column-shaped solder joints and chip after 1400, 2000, 2400, 2800, 3200, 3400 and 3600 temperature cycles, respectively, under the second temperature cycling condition. We can see from Figure 4.6 that some parts of the solder joints had faded or were not present at all after 2000 temperature cycles and gradually more and more areas became faded or were disappeared. Figure 4.7 shows the fractional crack area of solder joint and chip pad interface for the seven solder joints on a test chip at 1400, 2000, 2400, 2800, 3200, 3400 and 3600 temperature cycles.

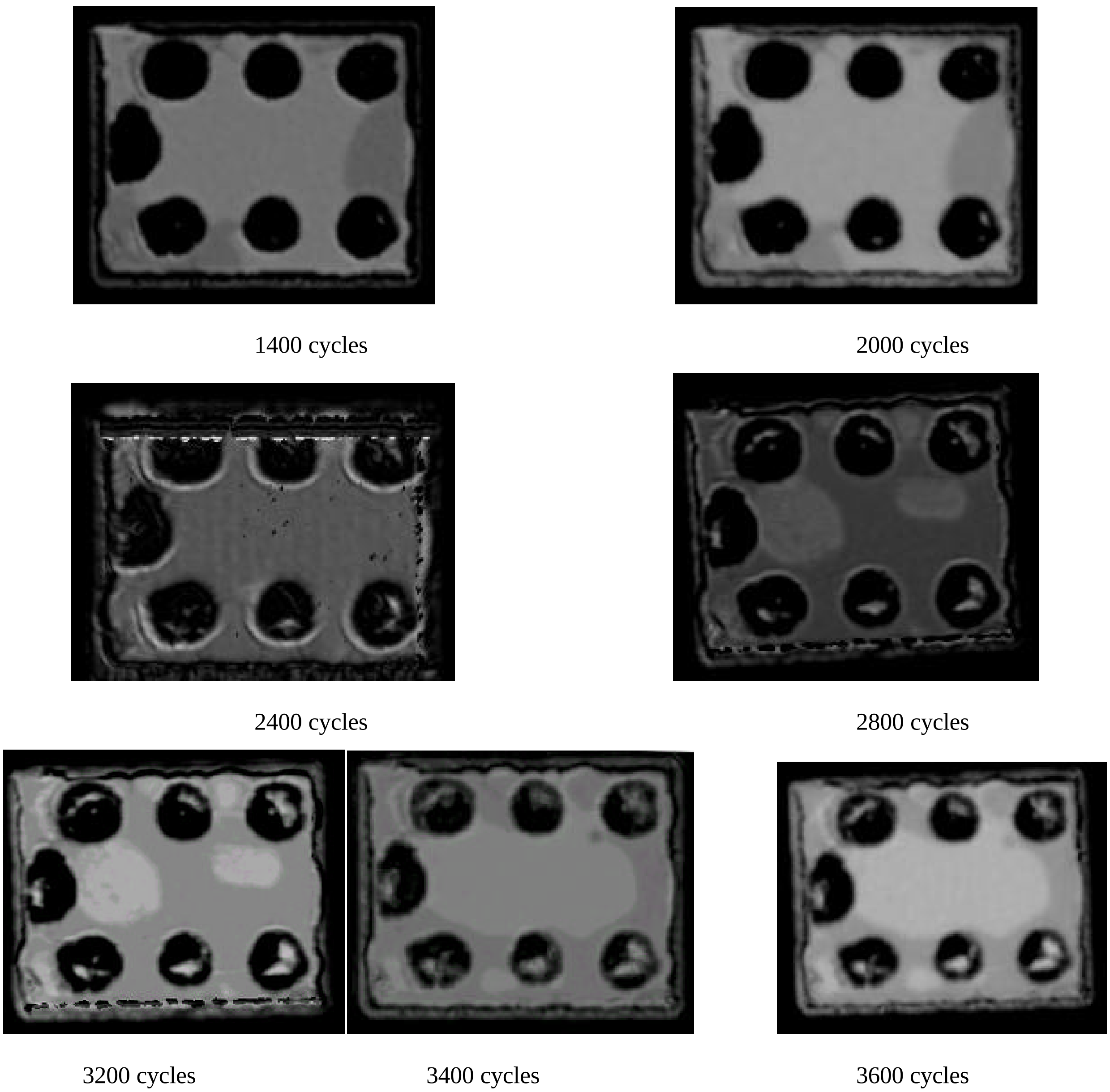


Figure 4.6. Typical C-SAM images of the interface between stacked hourglass/column-shaped solder joints and chip in FCOF assembly during temperature cycling.

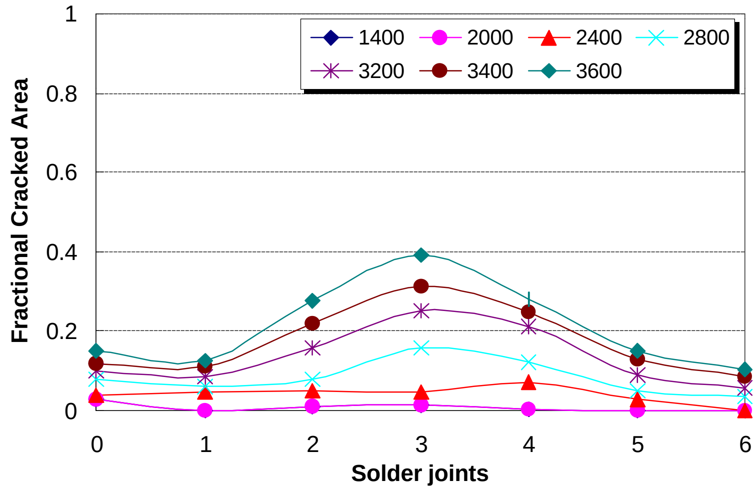


Figure 4.7. The fractional crack area of solder joint and chip pad interface for the seven solder joints on the FCOF assembly at different temperature cycles.

Figure 4.8 is a comparison of the average crack area increase rate of FCOF and FCOB assemblies with single bump barrel-shaped solder joints and stacked hourglass/column-shaped solder joints during temperature cycling under the second temperature cycling condition. It is obvious that crack area in FCOF assemblies increases slower than that in FCOB assemblies, especially for the single bump barrel-shaped solder joint case. Therefore, we can conclude that flex substrate slows down crack propagation rate and thus improve overall fatigue lifetime.

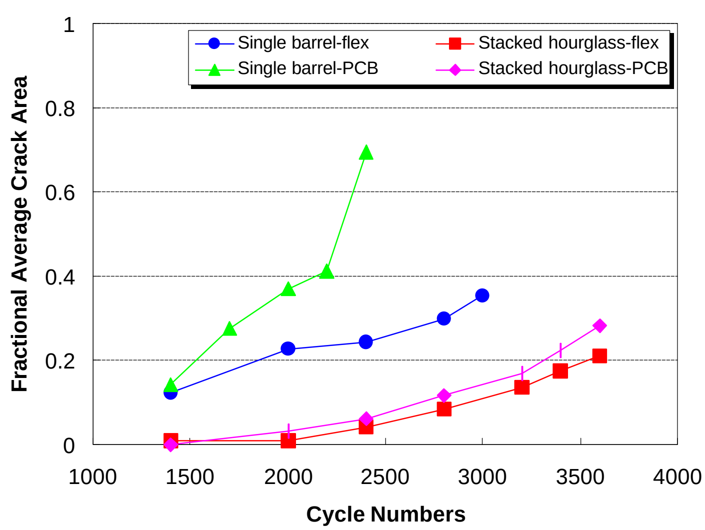


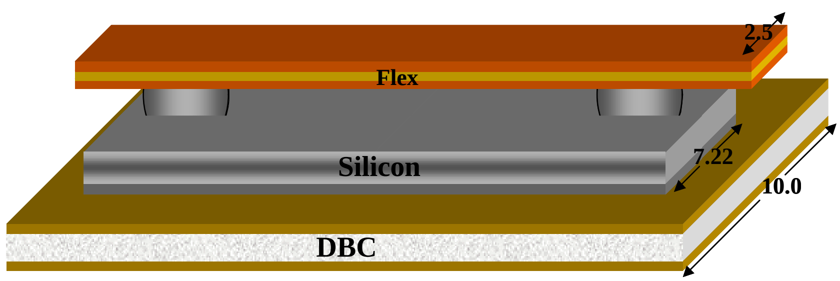
Figure 4.8. A comparison of the average crack area increase rate of FCOF and FCOB assemblies with single bump barrel-shaped solder joints and stacked hourglass/column-shaped solder joints during temperature cycling under the second temperature cycling condition.

4.3 Mechanism of Substrate Flexibility on Improving Solder Joint Reliability

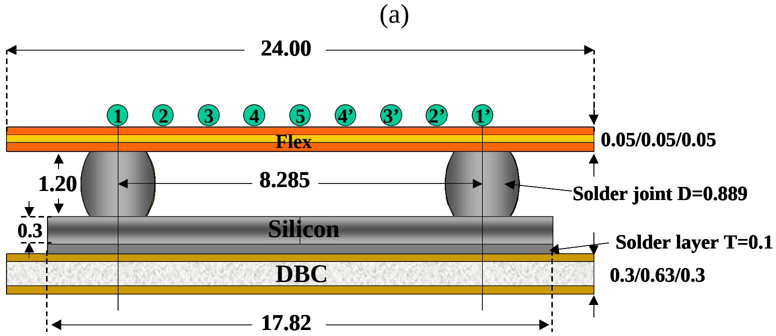
From section 4.2, we know that flip chip on flex assembly has longer fatigue lifetime than flip chip on rigid PCB assembly due to the compliancy of the flex substrate. This section is to investigate the flex substrate behavior during temperature cycling and study the mechanism of the substrate flexibility on improving solder joint reliability. Flex substrate behavior during temperature cycling were detected by probing different locations on the flex surface. Two kinds of sample configurations were investigated.

4.3.1 Sample Preparation

Two kinds of sample configurations were prepared and investigated. The first type of sample is illustrated in Figure 4.9. This is a one-dimensional flex strip sample. Silicon chip was attached to a direct bond copper (DBC) substrate using solder. Two solder joints located at the two ends of the chip were used to interconnect the chip and flex substrate. The flex was cut into a narrow strip so that we can treat it as a one-dimensional line to simplify the problem. The displacement of the flex during thermal cycling was probed only at the left five of the nine locations uniformly distributed along the flex strip, considering the symmetry of the nine points, as shown in Figure 4.9 (b). Two of such samples were tested.



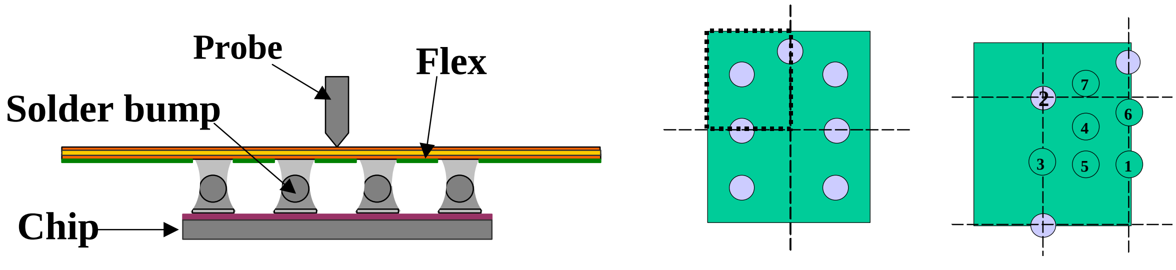
(a)



(b)

Figure 4.9. Schematic drawing of the one-dimensional flex strip sample. (a) 3-D drawing; (b) cross section.

The second type of test sample is a two-dimensional flex plate, as shown in Figure 4.10. This test sample configuration is exactly same as the samples for temperature cycling tests. There are seven solder joints on the test chip which make the interconnection between flex and chip. Considering the symmetry, only a quarter of the flex plate is investigated. Seven locations were probed as shown in Figure 4.10 (c). Again, two samples were tested.

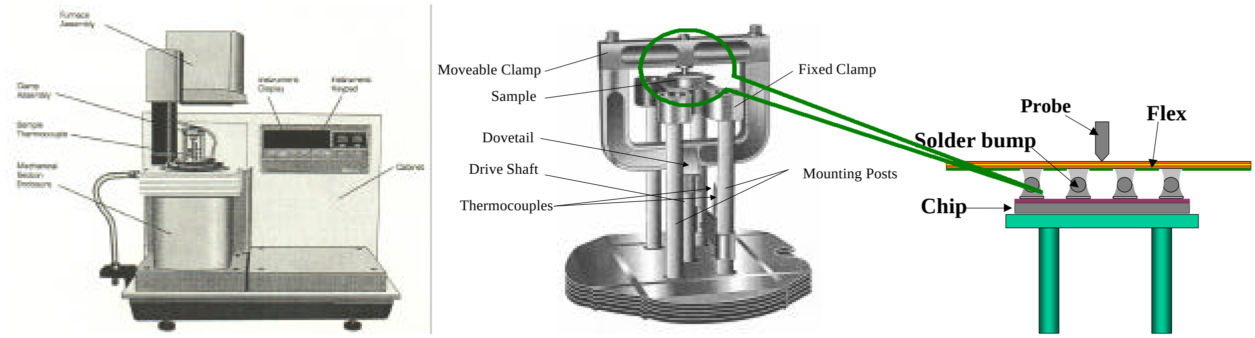


(a) (b) (c)

Figure 4.10. Two-dimensional flex plate test sample. (a) Cross-section view; (b) Top view; (c) Probe locations.

4.3.2 Flex Substrate Displacement Measurement

The TA Instruments Dynamic Mechanical Analyzer (DMA) 2980, as shown in Figure 4.11, is used to detect the behavior of the flex under thermal cycling. DMA is an analytical instrument used to test the physical properties of many different materials. The thermal mechanical analysis (TMA) controlled force mode is used to measure the displacement of a sample as a function of time, temperature, and applied force. Force can be applied in one of three manners: constant force, stepped force, or continuous force ramp. In our research, the static force is the force applied to the sample when the experiment is started. The clamp assembly of the DMA has fixed clamp and moveable clamp. On the moveable clamp, there is a probe which moves with clamp. The test sample is placed on the fixed clamp with the flex side facing up and the moveable clamp is above the sample, as shown in Figure 4.11 (c). Because we used static force mode, the probe is always in touch with the flex and moves with the flex to keep the force exerted on the probe constant. The static force of 0.005 Newton is used in our experiments. The DMA system monitors and measures the probe displacements dynamically during the operation. The probe displacement resolution is 0.01μm. Thus, we can know the displacement of the flex during temperature cycling from the displacement of the probe.



(a) (b) (c)

Figure 4.11. The TA Instruments Dynamic Mechanical Analyzer [1]. (a) The outlook; (b) Clamp assembly; (c) Magnified picture of probe and sample under test.

The thermal cycling condition used is:

Equilibrate at 30.00 °C, Isothermal for 3.00 min;

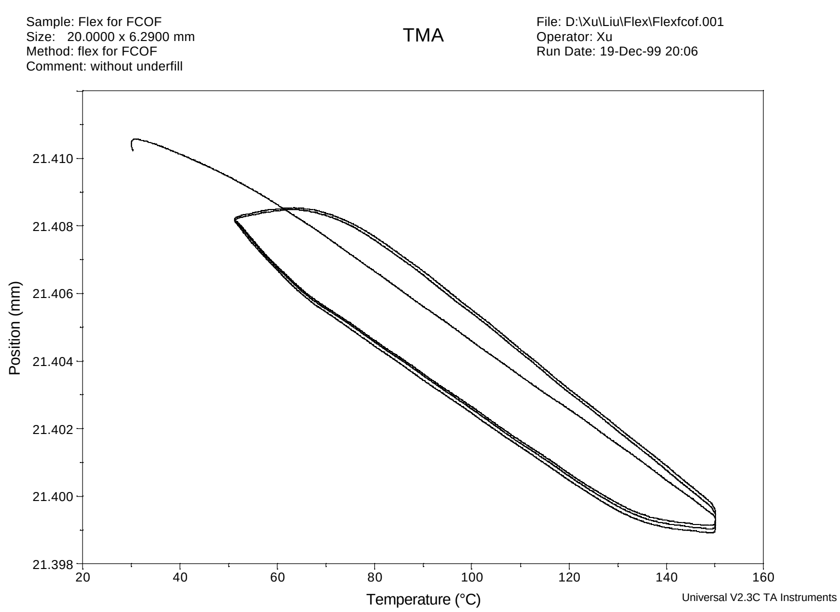
Ramp 1.00 °C/min to 150.00 °C, Isothermal for 10.00 min

Ramp 1.00 °C/min to 50.00 °C, Isothermal for 10.00 min;

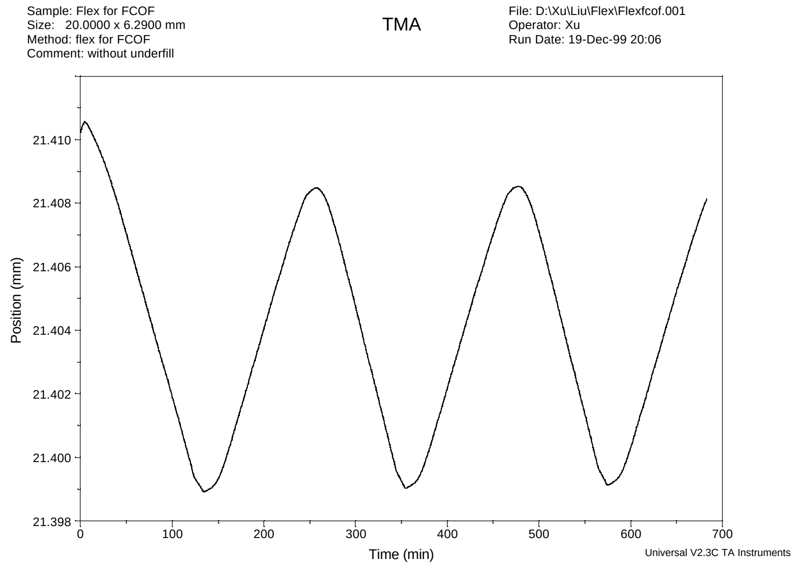
Repeat for 3 cycles

End of method

Therefore, the sample inside the DMA goes through three temperature cycles between 50 and 150 °C. A typical result for three heating/cooling cycles is shown in Figure 4.12.



(a)



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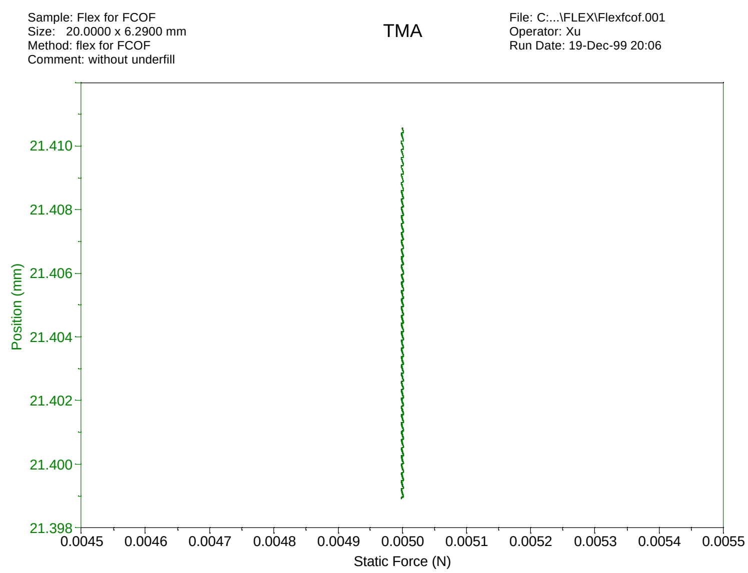


(c)

Figure 4.12. Typical TMA traces for flex deformation in a flip chip on flex assembly through three temperature cycles. (a) position vs. temperature; (b) position vs. time; and (c) position vs. static force.

4.3.3 Experimental Results

In this section, the TMA measurement results of the one-dimensional flex strip and two-dimensional flex plate are presented and analyzed.

4.3.3.1 Results on the One-Dimensional Flex Strip Samples

In the TMA test, the probe is placed at one point on the flex and the sample is under temperature cycling. Displacements can be measured as a function of temperature, time and applied force simultaneously. We are more interested in the flex displacement change as a function a time. Figure 4.13 shows a typical TMA trace of flex displacement in one flex strip sample through three temperature cycles. Note that the origin of the y-axis position of the DMA system is at the upper limit of the probe range, that is, when the probe goes up, the value of the y-axis decreases. As the temperature increases, the flex strip between the two solder joints moves up. The flex goes down when the temperature cools down. Therefore, during temperature cycling, the flex substrate deforms up and down. The initial heating cycle produces results that are different from those of the subsequent cycles. This difference is believed to be due to the thermal history of the flex and also to physical aging and other viscoelstic processes. Subsequent heating/cooling cycles are quite consistent indicating that reproducibility of the TMA method. The hysteresis loop is believed to be associated with the differential thermal lag, as it tends to vanish at slower heating/cooling rates [2].

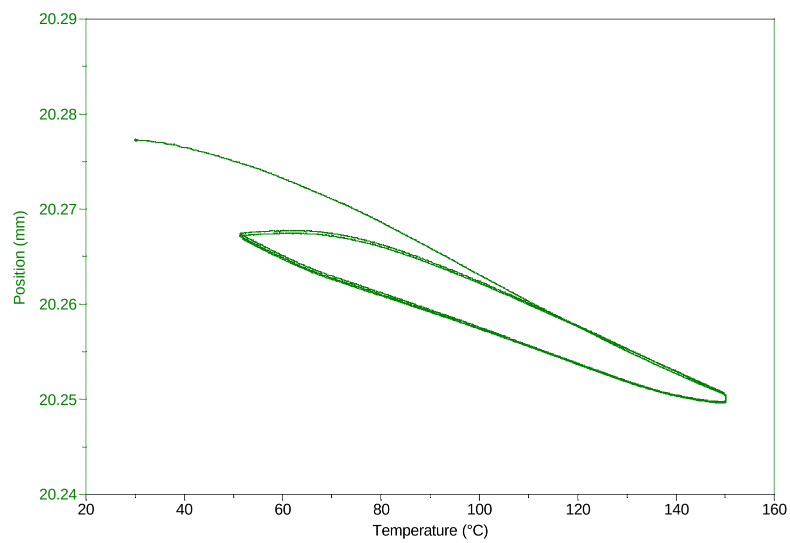
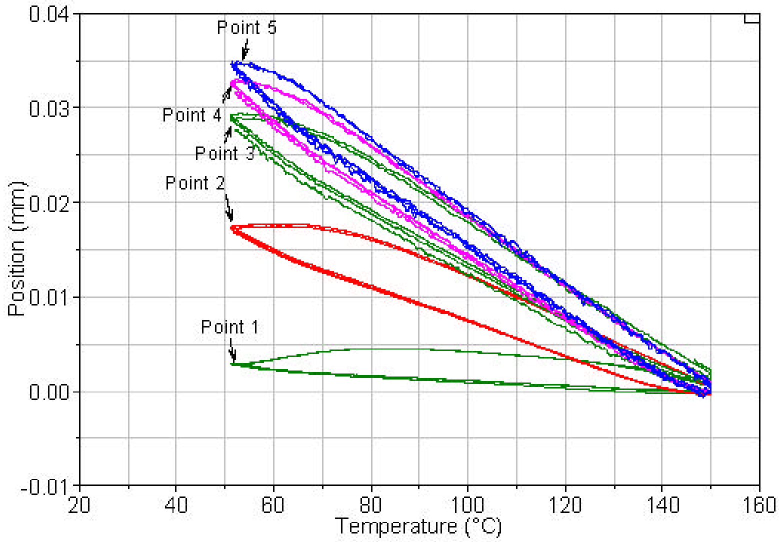
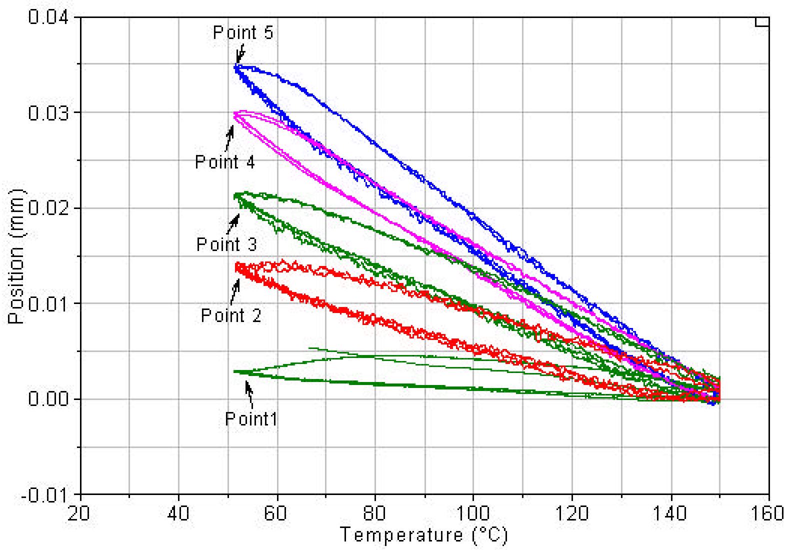


Figure 4.13. Typical TMA trace of flex displacement in one flex strip sample through three temperature cycles.

Figure 4.14 is the comparison of the flex displacements at different locations in the flex strip during temperature cycling for the two samples. Note that the TMA traces are calibrated for the DMA clamp system expansion during thermal cycling. We can see from the TMA curves that the flex has highest displacement at point 5 which is at the mid of the flex strip and has smallest displacement at point 1 which is right on top of the solder joint, with the points in between having displacements between those two values. Both of the samples showed the same trend that those locations closer to solder joints have smaller displacements and those locations farther away from the solder joints have higher displacements though the displacement value at one specific location may be different for those two samples. Figure 4.15 is the summary of the TMA test result for the one-dimensional flex strip samples. The displacement values at different flex locations in the figure are the average values of the two samples.



(a)



(b)

Figure 4.14. Comparison of the flex displacements at different locations in the flex strip during temperature cycling. (a) the first sample; (b) the second sample.

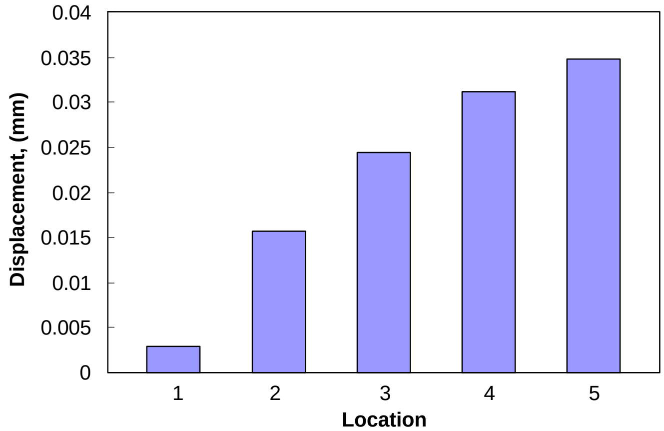


Figure 4.15. Summary of the TMA test result for the one-dimensional flex strip samples.

4.3.3.2 Results on the Two-Dimensional Flex Plate Samples

Figure 4.16 shows a typical TMA trace of flex displacement in a two-dimensional flex plate sample through three temperature cycles. Similar to the one-dimensional flex strip samples, flex moves up with the increasing temperature and goes down when the temperature cools down. TMA data show that for different locations on the flex, the displacement is quite different, as summarized in Figure 4.17. Note again that the TMA results are calibrated for the DMA clamp system expansion during thermal cycling. We can see that point 1 has the largest displacement, while point 2 has the smallest and those locations closer to solder joints have smaller displacements and those locations farther away from the solder joints have higher displacements.

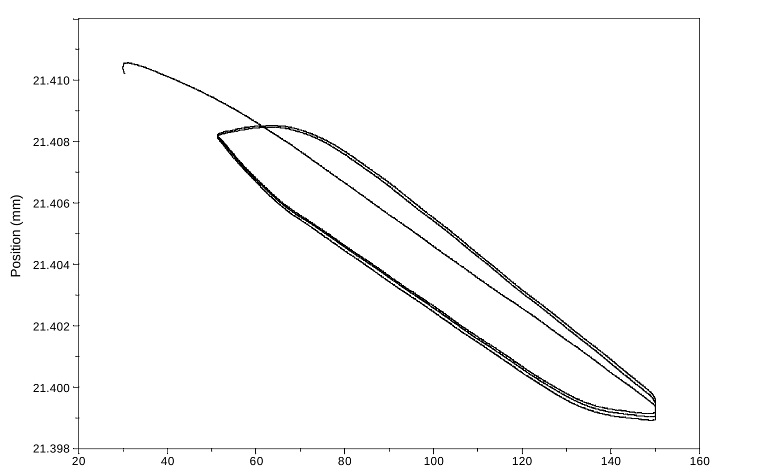


Figure 4.16. Typical TMA trace of flex displacement in a two-dimensional flex plate sample through three temperature cycles.

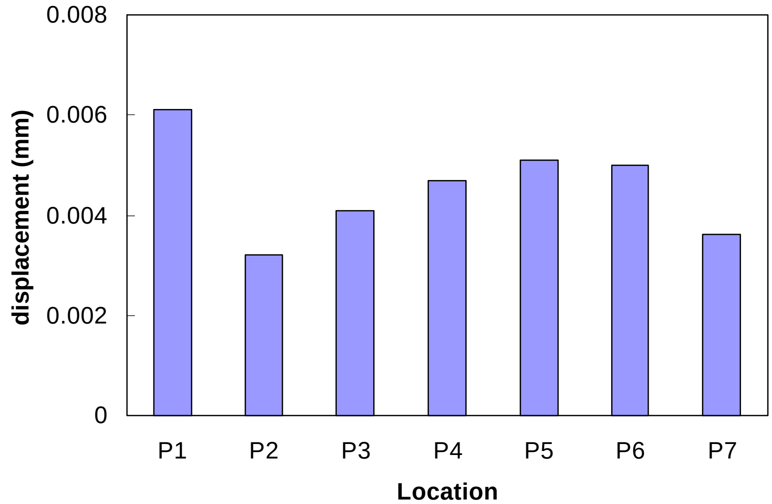
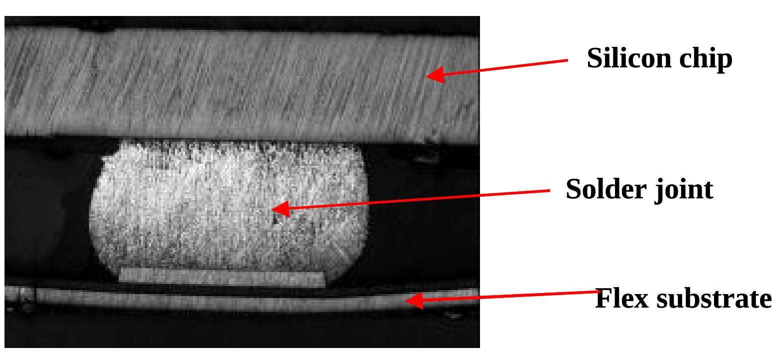


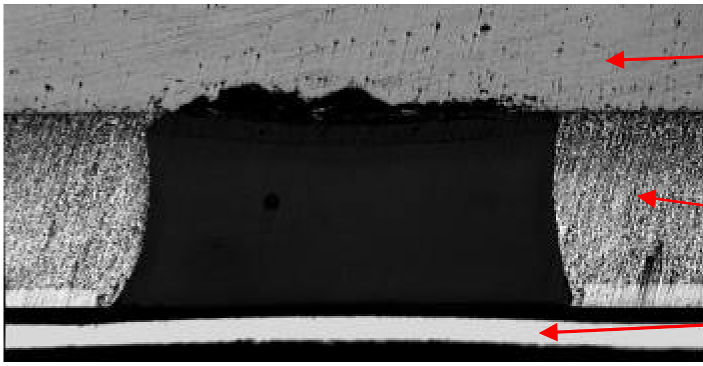
Figure 4.17. Displacement of flex at different locations during temperature cycle of 50°C and 150°C.

4.4 Discussion

The TMA results on flex behavior during thermal cycling strongly indicate that flex buckles during temperature cycling. The results can be interpreted satisfactorily if we regard solder joints are the fixed ends of the buckling and the flex in between the solder joints buckles downwards. We did observe flex buckling from the cross section of the flip chip on flex assemblies, as shown in Figure 4.18. As a result, the points that are closer to buckling center have greater displacements, while those closer to the fixed ends (solder joints) have smaller displacements. As the temperature increases, the flex between two solder bump joints becomes more and more flat because the flex expands more than chip, therefore, the probe goes up. On the contrary, when the temperature cools down, the flex between two solder joints buckles again and the probe goes down.



(a)



(b)

Figure 4.18. Cross section of flip chip on flex assembly showing flex buckling at room temperature. (a) Flex near one solder joint; (b) flex between two solder joints.

The phenomenon of flex buckling during thermal cycling could be explained when we consider the flip chip on flex structure assembling process and the mechanics of the assembly during temperature cycling process. The flip chip attach process is at elevated temperature to accomplish solder reflow, so the stress-free equilibrium state for the package is at the solidification temperature for the solder. Upon further cooling, due to the CTE mismatching between silicon chip and the substrate, the substrate tends to shrink more than the chip, thus there is strain and residual stresses built in solder joint interconnection after reflow process. The solder joints are deformed in a shear-dominant mode as shown in Figure 4.19. During thermal cycling, there is cyclic strain in the joint. This is the major mechanism of solder joint fatigue and failure. However, the situation is quite different if we attach flip chip assembly on flex substrate. When the reflowed flip chip on flex assembly cools down, the flex substrate shrinks more, just like rigid substrate, and thus the flex tends to pull the solder joints inward. In the other words, the solder joint try to pull the flex substrate outward, as demonstrated in Figure 4.20 (a). However, these tensile forces exerted by solder joints on the flex substrate are offset from the center of the flex substrate, and thus they induce bending moments on the flex, which in turn cause flex bending or buckling because the compliant characteristic of the flex. Furthermore, the bimaterial (the majority of the copper layer on the chip side is etched away) structure of flex substrate makes the buckling more evident. Actually, the mechanics situation for rigid substrate is the same, but because rigid substrate is much stiffer than solder, thus solder is deformed instead of rigid substrate. Figure 4.20 (b) illustrates exaggerated thermal bending of flex substrate in a flip chip on flex assembly.

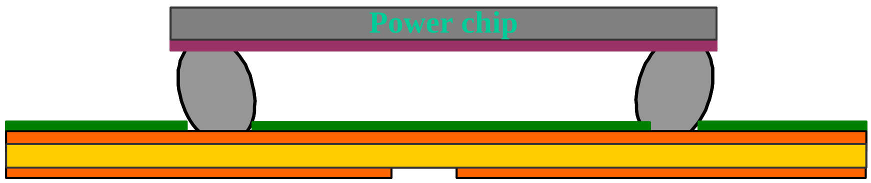


Figure 4.19. Schematic of exaggerated thermal displacements in flip chip on rigid board package.

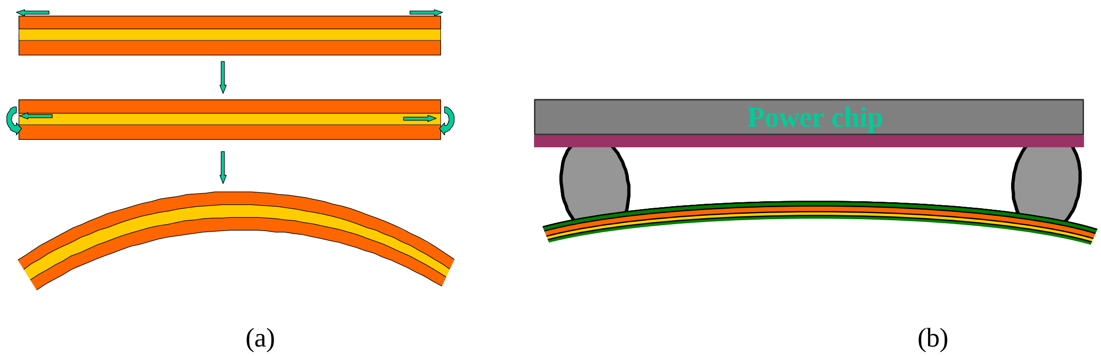


Figure 4.20. Flex buckling in flip chip on flex assembly. (a) The buckling mechanism; (b) Schematic of exaggerated thermal bending of flex substrate in flip chip on flex package.

As illustrated in Figure 4.20 (b), solder joint deformation and thus strain and stress in solder joint is much reduced because of the flex buckling. Therefore, solder joint reliability can be improved. This situation is very similar to the underfill encapsulant effect on flip chip assembly. Underfill encapsulant forces substrate (even rigid ones) bending and thus reduce thermal strain in solder joints [3]. Finite element analysis of flip chips on both ceramic and FR-4 substrates has obtained the same results that thermal strain can be reduced by bending of substrates by underfilling [4-5]. Our accelerated temperature cycling tests show that solder joint reliability is much improved by using flex substrate. Meanwhile, TMA results show that the compliant flex substrate deforms under thermal cycling. We believe that a certain amount of the thermal strain in solder joint is transferred to the compliant flex substrate and the flex substrate can absorb the strain and stress. Therefore, we attribute the reliability improvement of flip chip on flex assembly to flex buckling or bending under temperature cycling.

Finite element modeling showed that solder joint fatigue lifetime could be much improved by reducing die thickness and thus reducing the effective stiffness of the die and when die thickness approaching zero, the fatigue life goes to infinity [6]. Similarly, we believe that making the other side (substrate) of the solder joint compliant should also improve reliability. Actually, it was reported that flexing of substrate and die dissipates energy that otherwise would be absorbed by solder joints [6]. Hence, the worst case scenario for a solder joint occurs when the die and substrate each have a relative stiffness such that the amount of flexure in both is minimized. The maximum amount of energy is then absorbed by the solder joint, resulting in the lowest fatigue life.

4.5 Conclusion

The effect of substrate flexibility on solder joint reliability has been studied. Temperature cycling results showed that the thermal fatigue lifetimes of both single bump barrel-shaped and stacked hourglass/column-shaped solder joints were improved by using flex substrate. Thermal mechanical analysis with static force mode of Dynamic Mechanical Analyzer system was used to monitor the flex behavior during thermal cycling and it was found that flex substrate buckles during temperature cycling. It was indicated that the thermal strain and stress in solder joints could be reduced by flex buckling or bending and flex substrate could absorb the strain and stress. Therefore, we attributed the reliability improvement of flip chip on flex assembly to flex buckling or bending under temperature cycling.

4.6 References

[1] TA Instruments Dynamic Mechanical Analyzer (DMA) 2980 manual, TA corporation.

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