Evaluation of Raw Substrate Variation from Different Suppliers and Processes and their Impact on Package Warpage

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Abstract

Thin substrates have been used in more and more package-on-package (PoP) designs to meet the overall package thickness requirement. Low CTE cores are becoming more popular to reduce thin package warpage. On the other hand, substrates used in the same product are often sourced from multiple suppliers. Packages built with thin substrates sourced from different suppliers were found to have different end-of-line (EOL) package warpage. In this paper, 5 legs of substrates from 3 different suppliers were studied and compared with regard to raw substrate warpage, raw substrate modulus and CTE properties, and their reactions to 1x reflow thermal conditioning in order to understand any correlation to end-of-line package warpage. It was found that raw substrates sourced from different suppliers, or different processes in the same supplier, could have different levels of initial bare substrate warpage due to residual stress. Simulation results showed clear correlation between bare substrate warpage and EOL package warpage. However, such correlation was not observed with the limited measurement data collected. It was also found that properties (CTE and modulus) of finished composite substrates from different suppliers and processes could vary significantly, especially in the high temperature range. The difference in properties could be correlated to the difference at end-of-line package warpage in some cases. Further more, the substrates from different suppliers or processes could change their warpage, modulus and CTE properties in different ways after 1x reflow temperature conditioning. The study shows that it becomes more and more important to have better quality control of substrates sourced from different suppliers as substrate becomes thin and low CTE core is used.

Introduction

The trend for the next generation package-on-package (PoP) is going thin. [1, 2] Thin substrates have been used in more and more designs to meet the overall package thickness specification. One of the main challenges for thin PoP is package warpage control because the warpage tends to increase as the package becomes thinner and be increasingly susceptible to substrate variations. The increased package warpage and variations may lead to failure during SMT board assembly and low yield. As a result, package warpage control is becoming more and more critical. [3, 4]

As a standard business practice, substrates used in one product are often sourced from multiple suppliers. One problem that has been observed is that significant variation of end-of-line (EOL) package warpage can be found for packages using substrates from different suppliers, even though the same specifications are followed by these suppliers. As the test vehicle studied in this paper, a PoP package used substrates sourced from 3 different suppliers (Supplier A, B, C). In addition, two slightly different processes were used by supplier A (Process A and B). Figure 1 shows the EOL package warpage measured by shadow moiré for the packages built from these various substrates. The data shows about 15um warpage difference at room temperature, and more than 20um warpage difference at reflow temperature. The warpage variation at reflow temperature is the major concern as a 20um variation is significant enough to push some packages out of a typical 80um warpage spec.

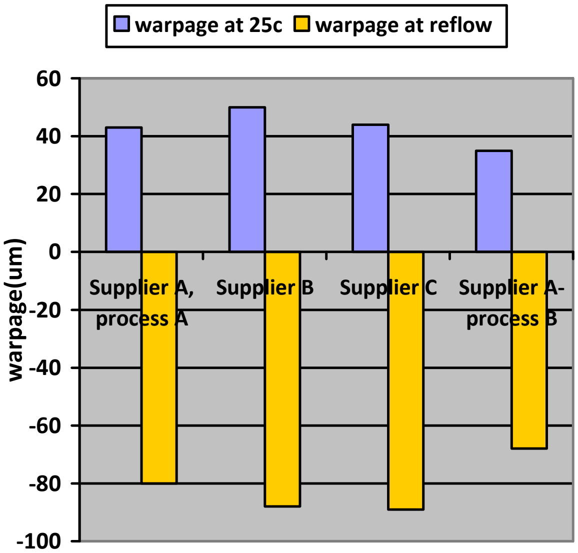

Figure 1. EOL package warpage variation

Since all of the other parameters were the same for these packages, it was intuitive to think that the EOL package warpage variation could be attributed to the different characteristics of these substrates as they came from different suppliers and/or with different manufacturing processes.

Below are a few possible factors that could make thin and low CTE substrate more sensitive to any variation in supply chains.

Firstly, as substrate becomes thinner and thinner, the core is no longer dominant in the whole substrate. Figure 2 is an example of a 0.13mm 2 layer substrate with 0.06mm core. The core is only 45% of the total substrate in terms of volume percentage, and the other 55% are copper traces and solder mask. As a result, the overall substrate characteristic is more sensitive to any variation in each layer.

Secondly, low CTE core substrates have been developed and widely used as one of the major solutions to reduce

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warpage of thin package. However, compared to a standard CTE core, low CTE core has more CTE mismatch with other materials used in the substrate, such as copper trace, buildup dielectric, and solder mask. As a result, more residual stress from the laminating process can be built up within the raw finished substrate that uses a low CTE core. Finished bare substrate is also more prone to warp due to the same reason. The level of residual stress and initial bare substrate warpage can be more dependent on a supplier's laminating process. Thus variations in different suppliers' process may lead to more variation in finished substrate's initial condition.

	Volume Percentage	
Substrate Thickness	0.3mm	0.13mm
Core (+prepreg)	70%	45%
Cu+ Solder mask	30%	55%

Figure 2 Volume percentage of each layer for thin substrate

Lastly, it is important to mention that how stable a substrate will be after the thermal conditions of package assembly processes may cause the difference in EOL package warpage as well, because substrates from different suppliers may change their properties and characteristics in different ways after going through the same assembly process condition.

The purpose of this paper is to evaluate the differences of substrates from multiple suppliers and their processes. The differences in substrates are then compared to the package EOL warpage variation to understand any correlation between them. The attributes being evaluated in this paper include the initial warpage of incoming raw substrates, the material properties (DMA, TMA) of incoming raw substrates, and the warpage and properties after going through a reflow temperature profile. In the following sections, the test vehicle package and substrate will be first described with the evaluation matrix defined. Detailed measurement data is presented and discussed next, followed by the summary and conclusion.

Test Vehicle

The package chosen as the test vehicle for this study was a 12mm package-on-package (POP) bottom package. The substrate was a 2 layer design with a 0.15mm core and a 0.23mm total substrate thickness. The core material used in the substrate was a low CTE type. The package and substrate are shown in Figure 3.

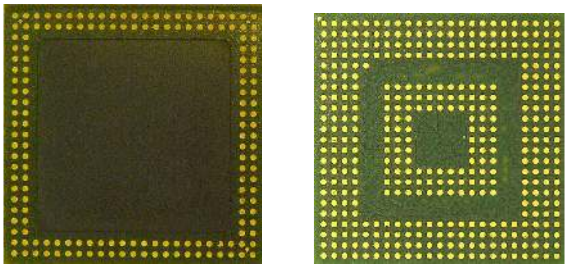


Figure 3. Package and substrate as the test vehicle

The substrate for this package was sourced from three different suppliers: Supplier A, B, and C. For supplier A, two slightly different processes (Process A and B) were used and were both evaluated for comparison. Another substrate with the same design but a different core material (ultra-low-CTE core) was also sourced from Supplier A to see what effect the core material would have. The complete evaluation matrix is listed in Table 1.

Leg	Supplier	Process	Core material
1	A	A	POR
2	B		POR
3	C		POR
4	A	B	POR
5	A		B (ultra-low CTE)

Table 1. Substrate Evaluation Matrix

For each leg, the following data was measured and compared:

(1) End-of-line (EOL) package warpage
(2) Incoming bare substrate (as is) warpage
(3) Bare substrate warpage after going through a 260C temperature profile one time (1x).
(4) Modulus (DMA) of incoming raw substrate (as is)
(5) Modulus (DMA) of substrate after going through a 260C reflow profile one time (1x).
(6) CTE (TMA) of incoming raw substrate (as is).
(7) CTE (TMA) of substrate after going through a 260C reflow profile one time (1x).

End-of-line (EOL) package warpage as well as bare substrate warpage were measured by shadow moiré at different temperatures ranging from 25C to 260C. DMA data was measured with 3-point bend mode for the finished composite substrate from -60C to 260C. TMA data was measured with extension mode from -60C to 260C using the finished composite substrate samples.

Bare Substrate Warpage Data

Figure 4 shows the comparison of the measured bare substrate warpage of the 5 legs. The bare substrates were not flat, and were actually quite warped (as much as 100um warpage for low CTE core legs and 160um for ultra-low CTE core leg). The warpage also changed with temperature and followed the same trend as package warpage, i.e., crying warpage at room temperature and smiling warpage at reflow temperature except for Leg 5 (ultra low CTE core). Major findings from the above data were:

(1) More than 20um of warpage difference was observed for substrates from different suppliers.

(2) There was also a significant difference in warpage at room temperature between the two legs of different processes from supplier A.

(3) The substrate built with the ultra-low CTE core (Leg 5) had a totally different warpage characteristic from the ones built with a low CTE core. It kept a smiling face warpage direction throughout the tested temperature range from 25C to 260C, and had as high as a 160um warpage at 260C.

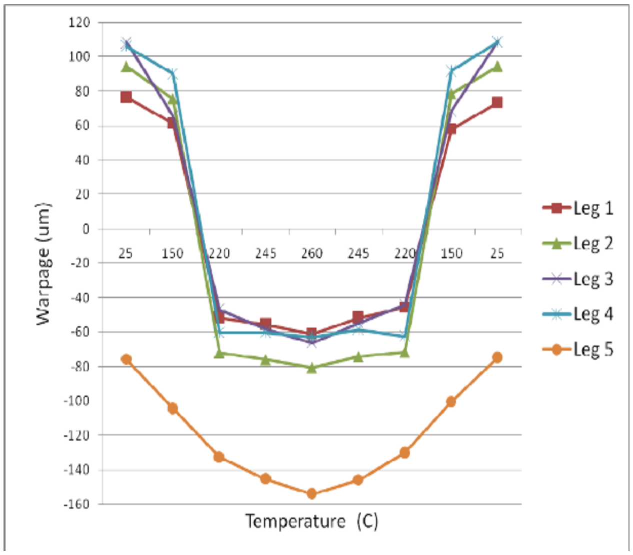
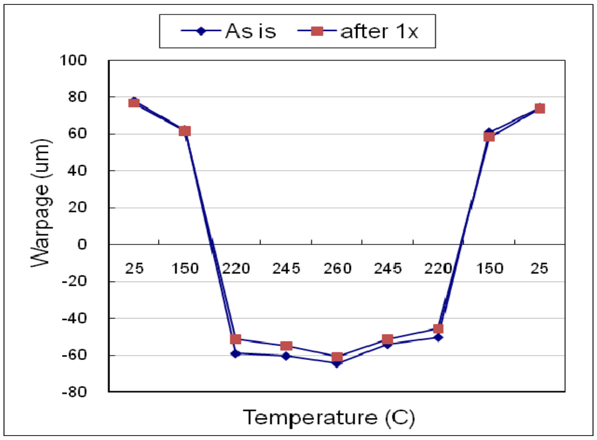
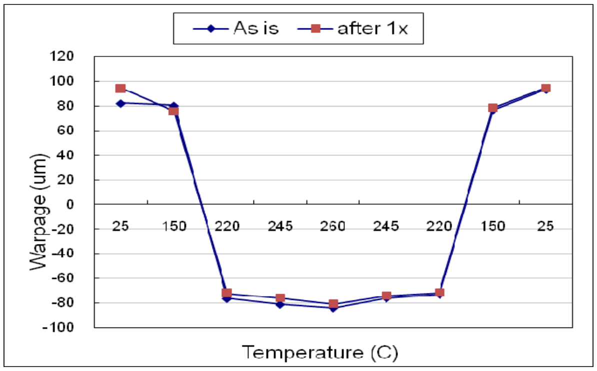


Figure 4. Warpage of bare substrate

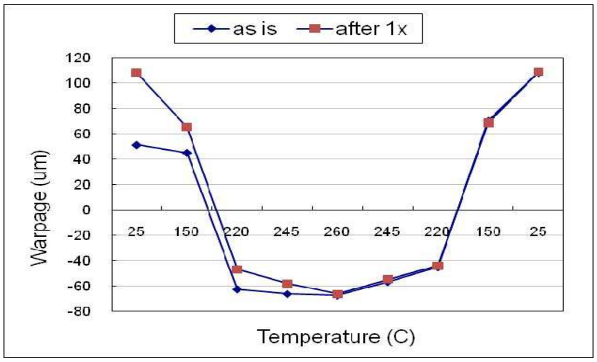
To access how the bare substrate warpage was affected by thermal conditioning for each leg, the same samples were measured again after going through a 260C temperature measurement profile (1x data). They were compared to the original measured data (as is data), as shown in Figure 5 for each leg.



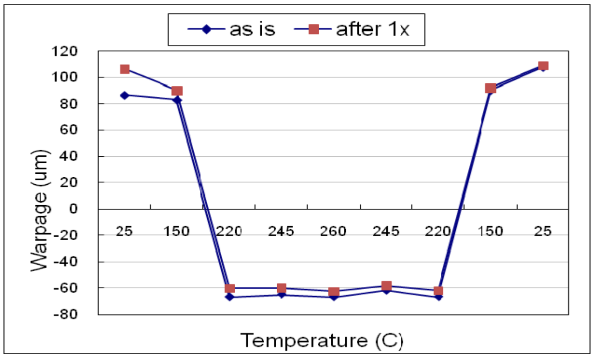
(a) Leg 1



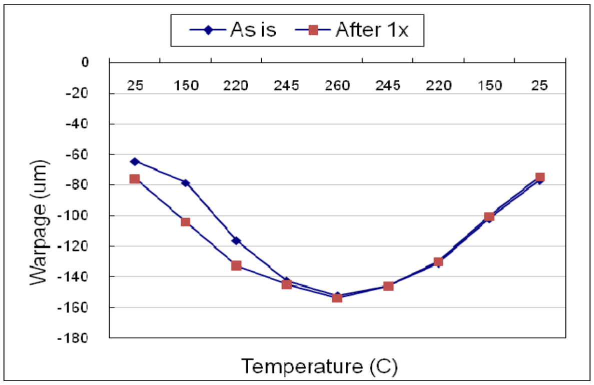
(b) Leg 2



(c) Leg 3



(d) Leg 4



(e) Leg 5

Figure 5. Bare substrate warpage comparison for the as is and 1x reflow condition

For low CTE core substrates (leg1-4), it was found that the warpage of the substrate from supplier C was more unstable. Its warpage changed significantly from the as is condition to the 1x reflow condition. The warpage for the substrates from supplier A and B was more stable except for some changes at room temperature from the as is to 1x condition. The warpage of the substrate built with ultra-low CTE core (Leg 5) also showed some significant difference from the as is to 1x condition. This data indicates that substrates from different suppliers can have different sensitivities to thermal conditions as they go through the package assembly steps; therefore, resulting in different package warpage at the end-of-line.

Correlation of bare substrate warpage to EOL package warpage

Finite element models were used to understand the impact of a warped substrate on the end-of-line package warpage. In this study, a flat substrate was compared to a warped substrate. All of the other package parameters were assumed to be the same for these two cases. The package warpage was calculated from the finite element model for these two cases, and is shown in Figure 6. The model result showed that the package warpage was higher if a warped substrate was used, assuming all the other parameters were the same.

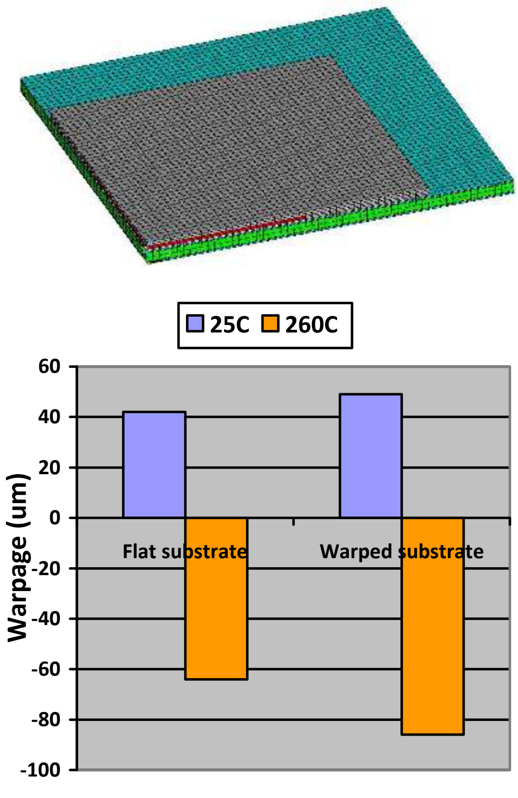


Figure 6 FEM warpage model study

However, the measurement results presented in the last section were mixed in terms of correlation between bare substrate warpage and EOL package warpage. In Figure 7, the measured end-of-line package warpage was compared against the measured bare substrate warpage from Leg1 to Leg4. The comparison indicates no clear trend for the correlation between bare substrate warpage and EOL package warpage. But a conclusion should not be drawn from this limited data that there is no correlation between bare substrate warpage and EOL package warpage. This is because the EOL package warpage can be affected by other parameter variations in the substrates in addition to the bare substrate warpage. For example, the finished substrate material properties variation among these substrates, which is investigated in the next section, also have an important effect on the EOL package warpage and may mix up with the bare substrate warpage effect.

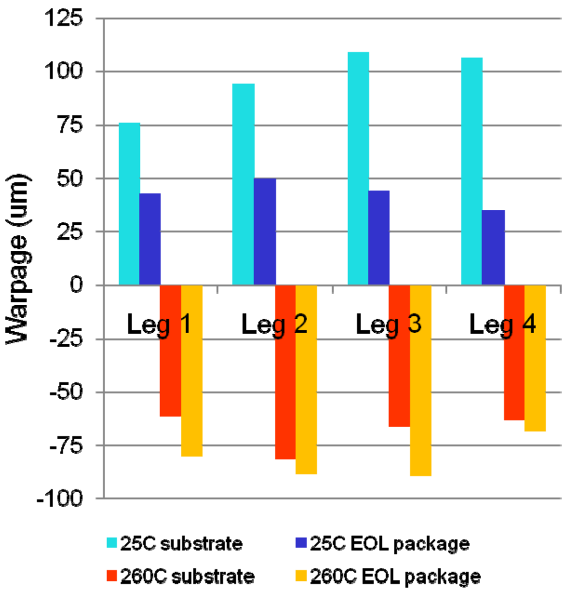


Figure 7. EOL warpage vs. bare substrate warpage

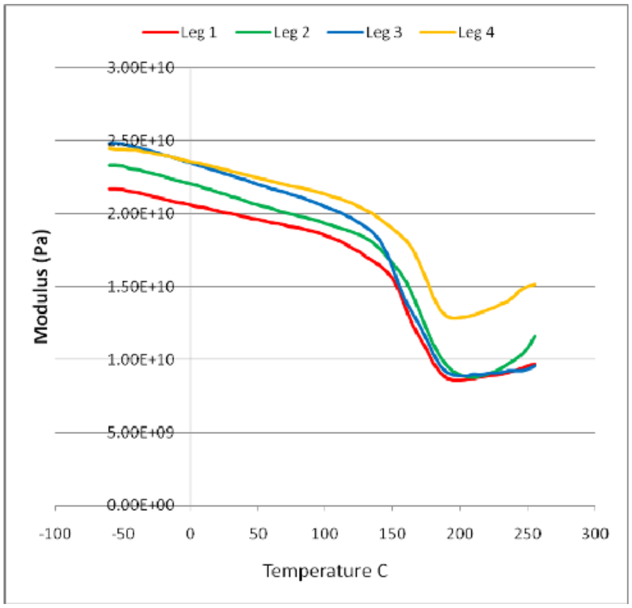


Figure 8. Modulus comparison of the 4 legs

Bare Substrate DMA Property Comparison

In addition to the bare substrate warpage, the material properties of the finished substrates from different suppliers were also measured and compared.

Figure 8 shows the DMA modulus comparison of leg1 through leg 4. Each leg had a different modulus curve. In particular, leg 4 had a significantly higher modulus at reflow temperatures than the other legs. Its higher modulus could be one of the factors contributing to lower EOL warpage of the package built with this substrate.

To evaluate the thermal condition effect on substrate modulus, DMA measurements were done at the as is and after 1x reflow conditions for all 4 legs. Figure 9 compares the modulus values for the two conditions at 25C and 250C. The data indicates Leg 4 substrate was also the one which had the most significant change in modulus at reflow temperature after 1x reflow. All of the other legs showed no significant changes in modulus values when tested as is or after 1x reflow.

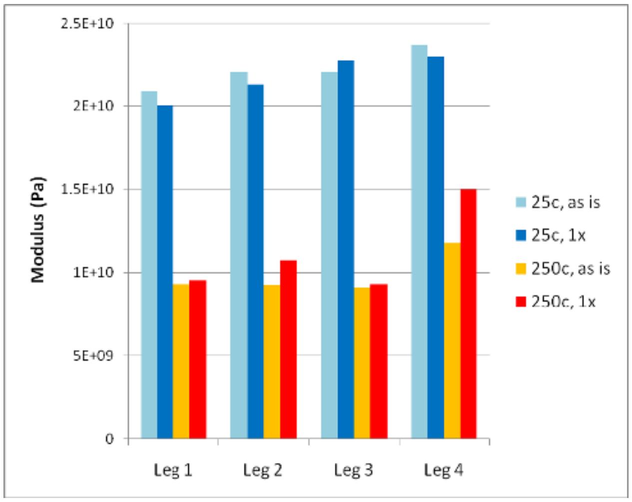


Figure 9. Modulus comparison for the as is and after 1x conditions

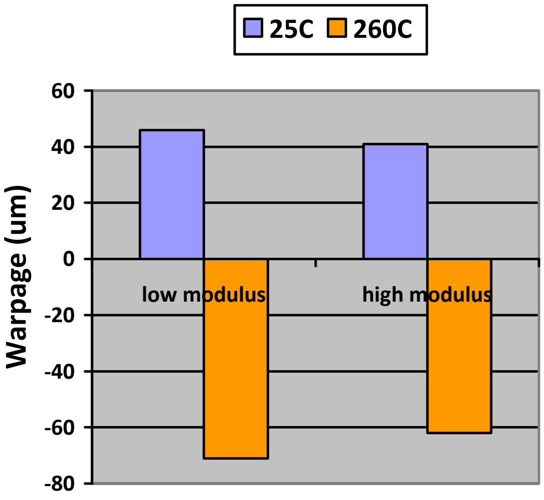


Figure 10. Simulation result for effect of substrate modulus

Warpage model simulation study also indicated that higher substrate modulus was beneficial for reducing package warpage, as shown in Figure 10. What was observed in the measurement data presented above was consistent with the simulation result.

Bare Substrate TMA Property Comparison

Coefficient of thermal expansion (CTE) is another important property of substrate which affects the package warpage. Figure 11 is the comparison of measured CTE of the 4 legs under the as is and 1x reflow condition. For each leg, CTE1 is the room temperature CTE (calculated from 50C-80C), and CTE2 is the reflow temperature CTE (calculated from 220C-250C). The measured data showed that, for CTE1, there was no significant difference among the 4 legs. There was also no much difference between the as is condition and after 1x reflow condition (except for Leg 2 with slightly more difference). However, for CTE2, Leg 1, 2, and 3 showed higher CTE after 1x reflow, while Leg 4 showed slightly lower CTE after 1x reflow. Leg4 had the lowest CTE2 (reflow temperature CTE) after 1x reflow conditioning. The data indicated 1x reflow thermal conditioning had a more significant impact on substrate property at high temperature than at room temperature, and the level of impact could be different depending on the substrate supplier and process. Because the substrate core is a fiberglass reinforced resin composite material, when going through reflow thermal profile, the epoxy resin material in the core is the main material which may experience property changes due to further curing as it goes through reflow temperature. More significant change in resin material property usually happens above its Tg temperature. The composite substrate CTE property is also more sensitive to any variation of modulus or CTE of epoxy resin at high temperatures.

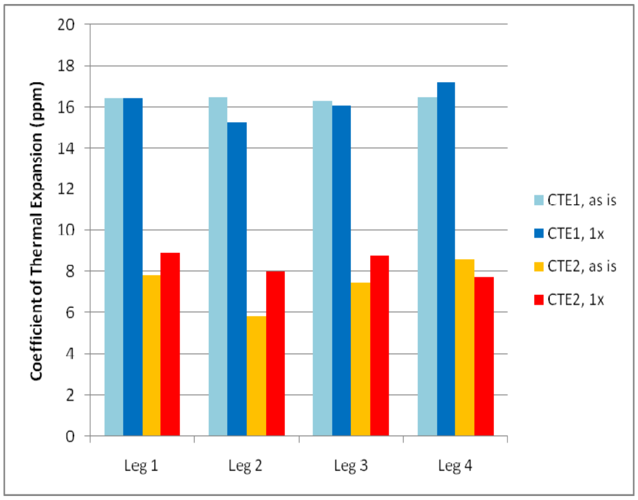


Figure 11. Measured CTE of the 4 leg substrates

Summary

Packages built with substrates from different suppliers were found to have different end-of-line package warpage. 5 legs of substrates from 3 different suppliers were studied and compared with regard to raw substrate warpage, raw substrate modulus and CTE properties, and their reactions to 1x reflow thermal conditioning in order to understand any correlation to end-of-line package warpage. It was found that:

(1) Raw substrates sourced from different suppliers, or different processes in the same supplier, could have different levels of initial bare substrate warpage. There was no clear trend of correlation between the bare substrate warpage and the EOL package warpage based on the limited measurement data collected, although the simulation result showed clear impact of bare substrate warpage. More data and study is needed in this area.

(2) The finished composite substrate properties (modulus and CTE) could have significant variation from different suppliers and processes, especially in the high temperature range. The difference of properties could be correlated to the difference at end-of-line package warpage in some cases. The leg with significant lower EOL package warpage was built from substrate which was measured to have higher modulus and lower CTE.

(3) The substrates from different suppliers or processes could change their warpage, modulus and CTE properties in different ways after 1x reflow temperature conditioning.

(4) The study shows that it becomes more and more important to have better quality control of substrates sourced from different suppliers as substrate becomes thin and low CTE core is used. However, since substrate variation is a combination of multiple factors, more studies should be conducted and more data should be collected to better understand how to access and mitigate the impact of substrate variation.

Acknowledgments

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