Using Element Birth and Death Technique in Modeling Cumulative Molded Substrate Expansion before Singulation

Jefferson Talledo[1*]

[1]*STMicroelectronics, Inc., Calamba City, 4027, Laguna, Philippines.*

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Short Research Article

ABSTRACT

Semiconductor packages are commonly assembled and molded in array format on a substrate strip before they are singulated into individual units. However, cumulative substrate expansion causes problems such as machine vacuum error or misaligned cut during singulation if the substrate expansion is not factored in. This study uses element birth and death technique in modeling the overall expansion of the molded substrate strip so that the predicted expansion could be considered in the singulation tooling design offsets. The expansion of the substrate was modeled with the different package assembly processes and thermal conditions. Modeling results showed that there is a cumulative increase in the length of the substrate as it passes through the different processes. The results are in agreement with actual substrate expansion prior to package singulation. This would not be captured when simulation is done only for the molded substrate without considering the cumulative contribution of the preceding processes. With the element birth and death technique in process-based thermomechanical modeling, substrate expansion could already be forecasted, and package assembly problems avoided.

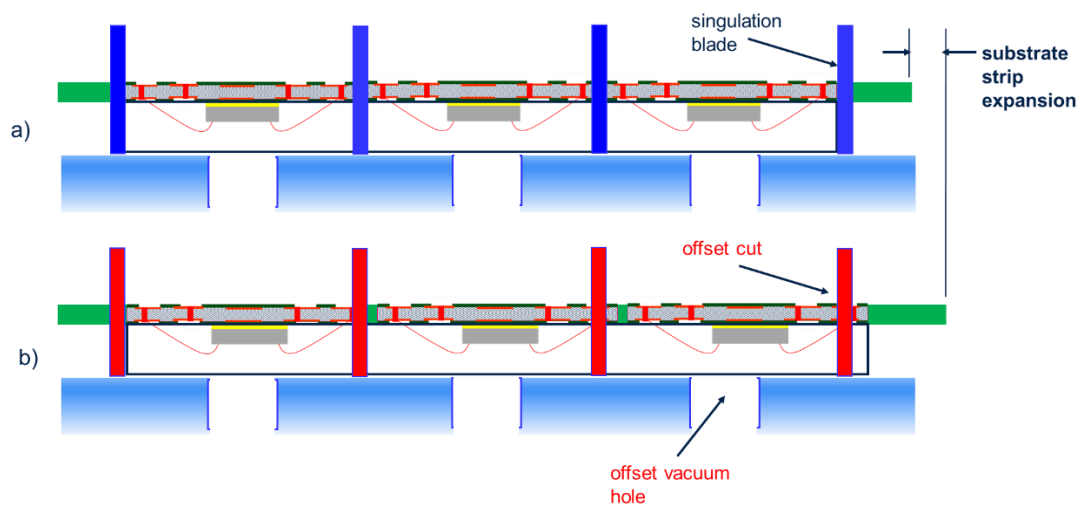*Keywords: Substrate strip; substrate expansion; element birth and death; modeling; singulation.*

**Corresponding author: Email: jefferson.talledo@st.com;*

1. INTRODUCTION

Saw singulation is an indispensable process to sever the mold array package (MAP) strips into individual units along saw streets using dicing blade [1]. It is the most challenging process to meet both quality and cost targets [2]. Saw singulation is an automated processing step between laser marking and final package inspection and sorting. It uses either conventional tape-mounting frames or advanced vacuum fixtures to hold each substrate during the cutting step. A typical problem associated with sawing accuracy during the singulation step is mechanical deformation such as substrate warpage or expansion caused by temperature and pressure variations in the molding and solder reflow processes [3]. In wafer level packaging (WLP) molding process, the die shift results from the combined effects of process parameters

including thermal contraction/expansion due to temperature changes during the process, mold flow drag force and mold compound curing shrinkage. Die shift causes misalignment during subsequent processes [4].

In this study, singulation problem due to molded substrate expansion is considered as shown in Fig. 1. The whole substrate strip is also shown in Fig. 2. Substrate expansion causes offset cut or misaligned cut. Vacuum leak or vacuum error with the machine vacuum fixture holding the strip could also be encountered when substrate expansion is not comprehended. The problem of molded substrate expansion could be solved by expansion compensation. However, there has to be a way to predict such expansion in order to incorporate the required compensation value even before the actual semiconductor is assembled.

Fig. 1. Molded substrate strip during singulation: a) ideal condition, b) with substrate expansion
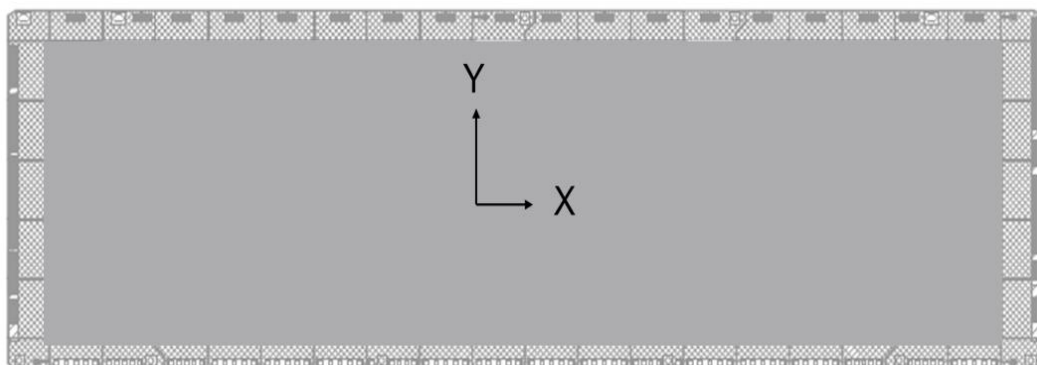
Fig. 2. Whole substrate strip

Substrate expansion modeling using element birth and death technique is one method that could be used to predict substrate expansion accumulated after each package assembly process step. In the element birth and death approach, an element can be deactivated or reactivated. A deactivated element remains in the model but contributes a near-zero stiffness value to the overall matrix. It also contributes nothing to the overall mass matrix and any solution-dependent state variables such as stress and strain are set to zero. An element can be reactivated only after it has been deactivated. Reactivated elements have a zero strain state [5].

Processes-based multistep simulation methods based on element birth and death technology are widely adopted to make simulation results more reliable and accurate [6]. This technique was used to evaluate warpage behavior of double-sided rigid-flex board assemblies during reflow soldering process [7] and to simulate the dynamically changing thermal properties of copper during the sintering process [8]. Element birth and death technique was also explored in 3-D modeling of through-silicon-via (TSV) with sidewall scallops in finite-element analysis (FEA) to evaluate and improve the thermo-mechanical reliability. Compared with the classic FEA, the method takes into account the process sequence and, hence, can accurately characterize the stress distribution and fluctuation phenomenon of TSVs, which agrees pretty well with X-ray experimental data [9]. Several studies [10-13] utilized element birth and technique and include simulating sequential processes for ball grid array (BGA) packages, strain distribution in ceramic multilayer capacitors during wave

soldering and reflow soldering, phase change of solders, and to further study the residual stress after reflow welding of BGA solder joints. Element birth and death technique was employed to simulate wafer molding process in a continuous manner and warpage during a typical RDL-first (redistribution layer first) fan-out panel level package (FOPLP) process [14-15]. Element birth and death technique is even used in welding simulations [16-18].

2. SUBSTRATE EXPANSION MODELING

Modeling using finite element analysis (FEA) with element birth and death technique was applied to simulate the cumulative substrate strip expansion. The main package assembly processes that could contribute to substrate expansion were considered in the modeling. Fig. 3 shows the typical package assembly process flow used to manufacture a semiconductor package from a substrate strip. A bare laminate substrate is commonly used, and silicon dies are bonded on it during the die attach process. It is then followed by the die attach curing process at 160°C. This is where the first significant substrate expansion is expected since it is done at higher temperature. The next significant substrate expansion is at molding and post mold curing at 175°C. After post mold curing, the molded strip is cooled down to room temperature for the succeeding processes. Before the package singulation process, the molded substrate strip would have an increase in its size or length due to the cumulative substrate expansion from preceding processes. This expansion prior to the singulation is the primary focus of the modeling.
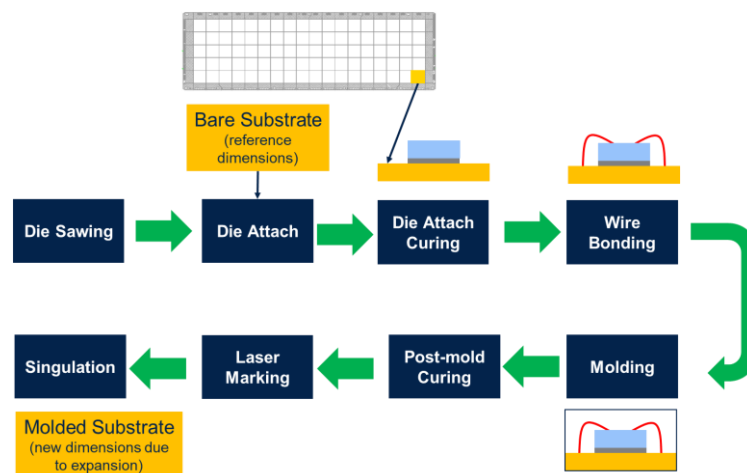

Fig. 3. Package assembly process flow

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2.1 Material Properties

In the modeling, linear elastic material properties were used for all the package component materials. The material properties are indicated in Table 1. As shown, some of the package components have temperature-dependent material properties. The properties below the glass transition temperature (Tg) are different from the properties above Tg. The coefficient of thermal expansion (CTE) is the material property that mainly dictates the amount of dimensional expansion of the material as it is heated. The CTE, modulus and Poisson's ratio are the material properties required as inputs for the substrate expansion modeling. These properties contribute to the overall substrate expansion behavior as the component materials are assembled together to form a semiconductor package.

2.2 Processed-based Modeling

The substrate expansion modeling was done using ANSYS, a popular FEA software used in thermomechanical modeling. The element birth and death technique was implemented using the EKILL and EALIVE commands in ANSYS. The EKILL deactivates the selected elements and the EALIVE activates whatever elements being selected. The stress-free or reference temperature was individually defined for each package component material using the MP, REFT command in ANSYS.

The FEA quarter model of the molded strip is shown in Fig. 4. Since modeling the whole strip would involve large number of finite elements, a strip slice was used to reduce the computation time. Symmetry boundary conditions were applied to the strip slice quarter model and the bottom exposed side of the substrate was fixed in the thickness direction (Uz = 0) for all the modeled process conditions before molding.

The modeling started at die attach curing process where the substrate would expand as temperature increases to reach the 160°C curing temperature. This curing temperature used in actual package assembly manufacturing is based on the specific die attach material behavior and recommended by the material supplier as verified in actual evaluations. In this process, the die bonded on the substrate would not have full mechanical connection with the substrate until after the curing process where cross-linking of the die attach material happens. In the FEA model, all the elements of the mold compound, die attach, and die were "killed" or deactivated in this simulated die attach curing process. All the deactivated elements enter the state of zero mechanical properties and will not be participating in the solution. The loads and constraints on them will not be counted in the load matrix, and thus ignoring its effect on the system matrix.

Table 1. Material Properties used in Substrate Expansion FEA

Solder Material	Coefficient of Thermal Expansion or CTE (ppm/ °C)	Modulus (GPa)	Poisson's Ratio
Die	3.0	169	0.23
Die Attach Film (DAF)	CTE1 = 80; CTE2= 70 @ Tg = 128°C	1.7@ 25C; 0.57@ 100C 0.045@ 150C; 0.037@ 200C 0.038@ 250C	0.35
Epoxy Mold Compound (EMC)	CTE1 = 8; CTE2 = 32 @ Tg = 125°C	27/ 1.2	0.25
Solder Mask	CTE1 = 60 CTE2 = 130 @ Tg = 114°C	3.4	0.29
Substrate Core	CTE1 = 19 CTE2 = 8 @ Tg = 200°C	20	0.22
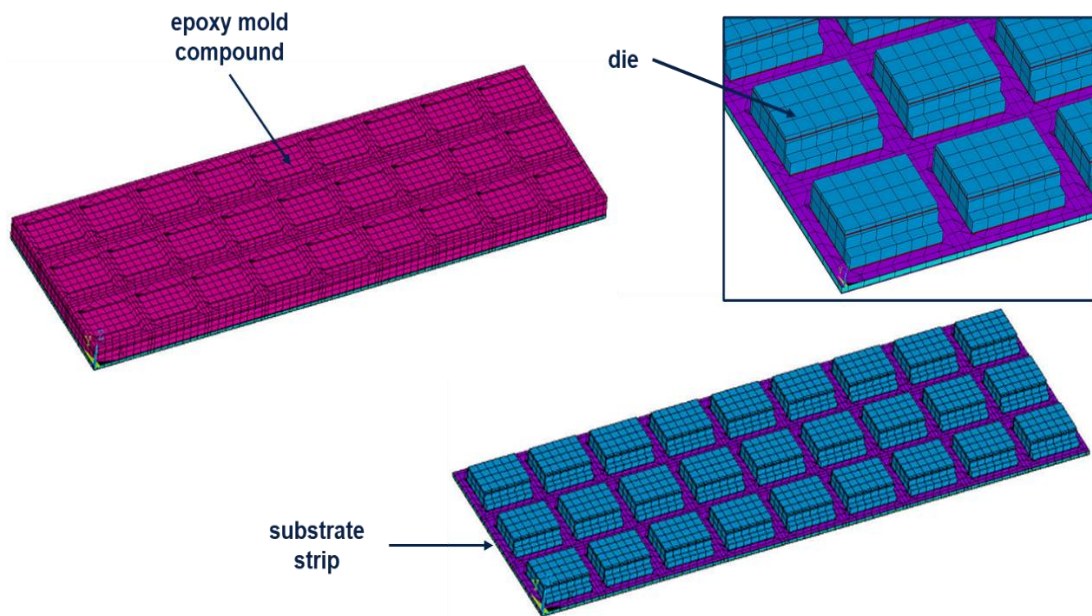
Fig. 4. FEA model of the molded substrate strip

During the cooling down to room temperature after die attach curing, the deactivated or "killed" elements of the die attach material and the die were reactivated. This was done because after die attach curing, both the die attach material and the die would have full mechanical interaction with the substrate strip as strong adhesion between the die attach and the substrate was established. The reactivated elements will restore the original mass, stiffness, and load values.
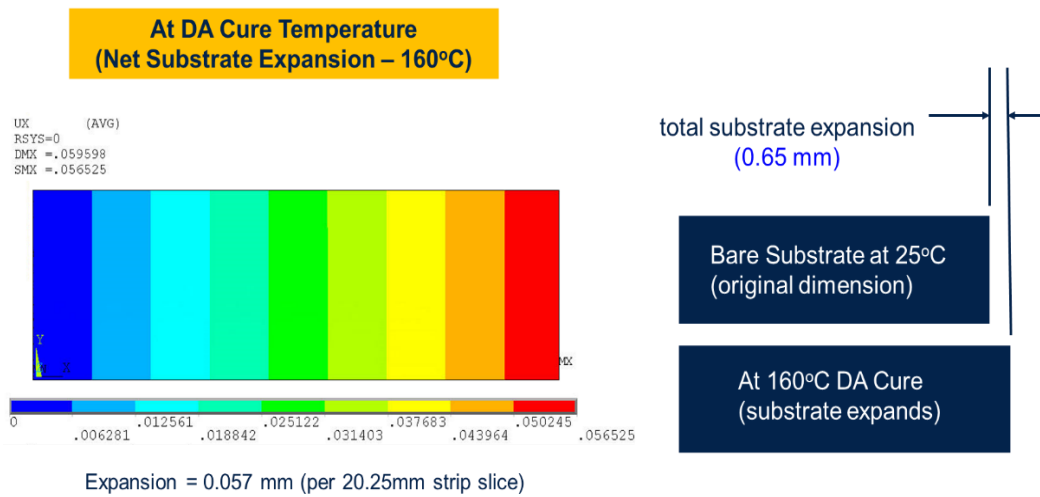
The next process step modeled was the post mold curing process where the substrate would again expand at the elevated mold curing temperature of 175°C. The mold compound material melts during the molding process and is expected to have no complete mechanical interaction with the die-bonded substrate until the mold material is fully cured after the post mold curing process. With that, the mold compound material was still "killed" or deactivated in the FEA model when analyzing the substrate strip expansion at 175°C. Only the substrate, die attach and dies were interacting before the mold compound material was fully cured.

After the post mold curing and during the cooling down to room temperature, the elements of the mold compound material were reactivated. In the FEA model, all the elements were interacting and included in the solution. There were no more "killed" or deactivated elements after the post

mold curing process as the mold compound was expected to be fully cross-linked and established full mechanical connection with the other package components. The reference temperature was set at 175°C for all the elements and the contraction result was subtracted from the net expansion from the previous step. The 175°C was chosen as the reference temperature as this is the post-mold curing temperature at which the molded substrate strip is considered stress-free or the thermal strain is assumed to be zero. The thermal strain calculations are performed relative to the reference temperature.

3. RESULTS AND DISCUSSION

With the length of the bare substrate at room temperature considered as the reference original dimension, Fig. 5 shows the expansion of the strip slice at 160°C die attach curing temperature. The total equivalent substrate expansion is around 0.65 mm. This is mainly dependent on the coefficient of thermal expansion (CTE) of the substrate. Higher CTE translates to higher expansion at the same change in temperature, which is in this case from room temperature to the die attach curing temperature. The result shows the expansion of the bare substrate when subjected to 160°C since the influence of the die attach and die is not yet in effect in this process being simulated.

At DA Cure Temperature (Net Substrate Expansion – 160°C)

UX   (AVG)
RSYS=0
DMX =.059598
SMX =.056525

total substrate expansion
(0.65 mm)

Bare Substrate at 25°C
(original dimension)

At 160°C DA Cure
(substrate expands)
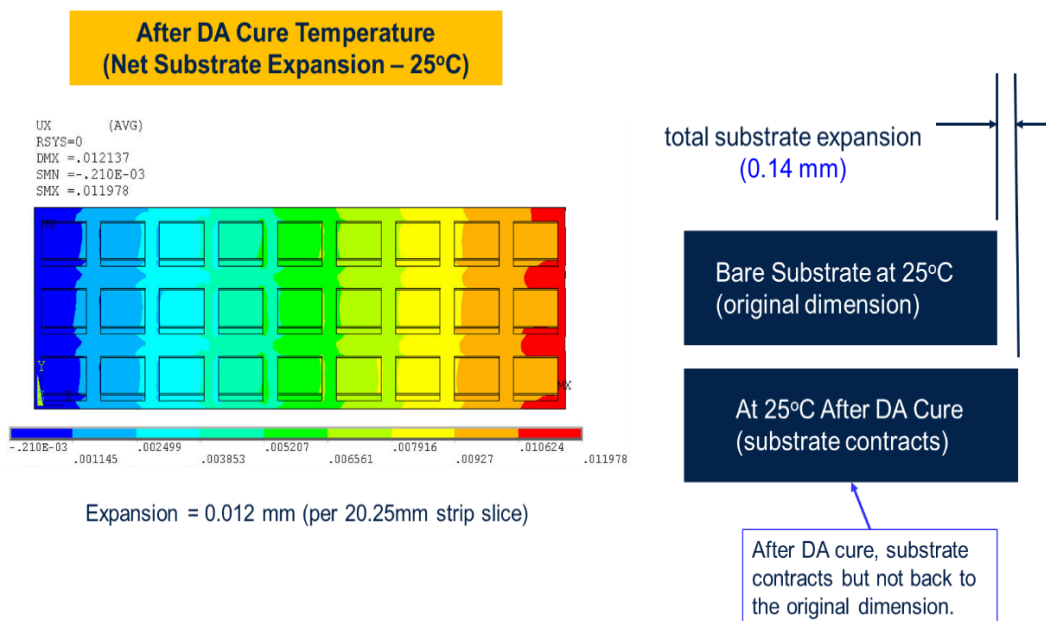
Expansion = 0.057 mm (per 20.25mm strip slice)

Fig. 5. Substrate expansion FEA result at die attach cure temperature

After die attach (DA) curing with the substrate being cooled down to room temperature (25°C), the substrate contracts as shown in Fig. 6. After the cooling down back to room temperature, the substrate did not return to its original dimension. It shows a net expansion of 0.14 mm. This implies that the presence of the die bonded on the substrate with die attach material cured at higher temperature has restrained the substrate from fully returning to its original state. This happens because the CTE of the die is much lower compared to that of the substrate. Duri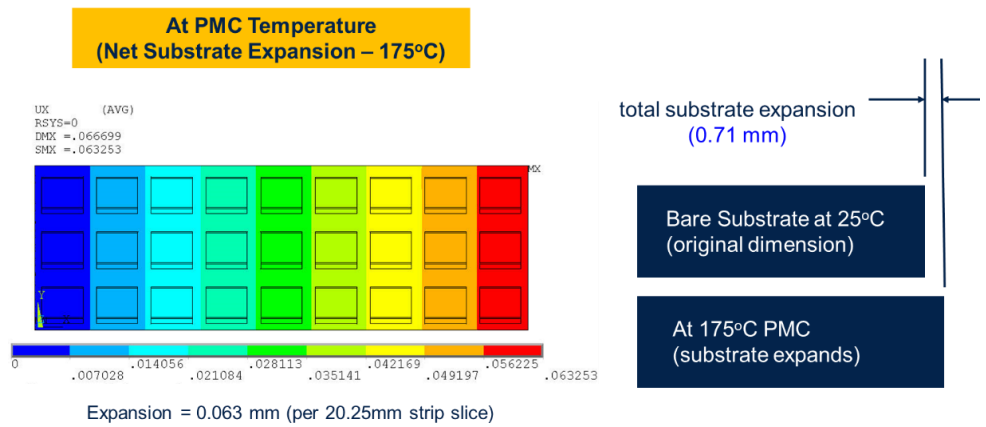ng cooling down, the contraction of the die could not match the contraction of the substrate. In effect, the substrate contraction back to its original state at room temperature is restrained because of the CTE mismatch.

When the substrate with die is heated during molding and maintained at the post mold cure (PMC) temperature of 175°C, the substrate expands again. Fig. 7 shows a total substrate expansion of 0.71 mm at PMC temperature. The mold compound material is not yet contributing to the substrate expansion in this process step simulated.

After DA Cure Temperature (Net Substrate Expansion – 25°C)

UX   (AVG)
RSYS=0
DMX =.012137
SMN =-.210E-03
SMX =.011978

total substrate expansion
(0.14 mm)

Bare Substrate at 25°C
(original dimension)

At 25°C After DA Cure
(substrate contracts)

After DA cure, substrate contracts but not back to the original dimension.

Expansion = 0.012 mm (per 20.25mm strip slice)

Fig. 6. Substrate expansion FEA result at room temperature after cooling down from the die attach cure temperature

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**At PMC Temperature
(Net Substrate Expansion – 175°C)**

total substrate expansion
(0.71 mm)

Bare Substrate at 25°C
(original dimension)

At 175°C PMC
(substrate expands)
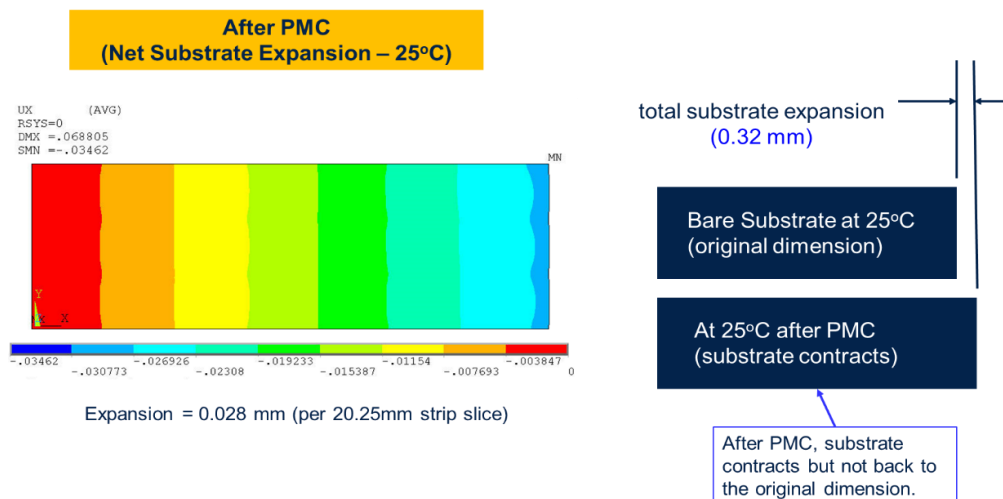
Expansion = 0.063 mm (per 20.25mm strip slice)

Fig. 7. Substrate expansion FEA result at post-mold cure (PMC) temperature

With the PMC completed, the mold compound would now contribute to the substrate expansion calculation. As shown in Fig. 8, the substrate contracts with the mold compound material during the cooling down of the molded substrate back to room temperature. The contour plot shows the contraction of the strip slice. However, result shows that it has not returned to its state at room temperature when the mold compound was not yet present. When the substrate at room temperature has no mold compound yet preceding the molding process, the total substrate expansion is at 0.14 mm. It can be seen that when the die-bonded substrate is molded, there is further increase in the total substrate expansion to 0.32 mm at room temperature.

The substrate expansion results are summarized in Fig. 9. It could be observed that there is a

consistent increase in the room-temperature net expansion of the substrate. This modeling observation also agrees with actual result as shown in Fig. 10 in terms of the presence of net expansion of the molded substrate before the singulation process. The simulated value from FEA modeling is just a bit higher and could be attributed to the fact that the material properties used are linear elastic only. Stress relaxation, that could happen in actual due to the viscoelastic behavior of the material, is not considered. However, results have revealed that the molded substrate strip that would go through the singulation process does not have the same dimension or length as the original bare substrate strip. If this net increase in length of the substrate is not comprehended in the tooling design, then issues during singulation could be encountered such as misaligned cut or vacuum leaks.

**After PMC
(Net Substrate Expansion – 25°C)**

total substrate expansion
(0.32 mm)

Bare Substrate at 25°C
(original dimension)

At 25°C after PMC
(substrate contracts)

After PMC, substrate contracts but not back to the original dimension.

Expansion = 0.028 mm (per 20.25mm strip slice)

Fig. 8. Substrate expansion FEA result at room temperature after cooling down from the post-mold cure (PMC) temperature
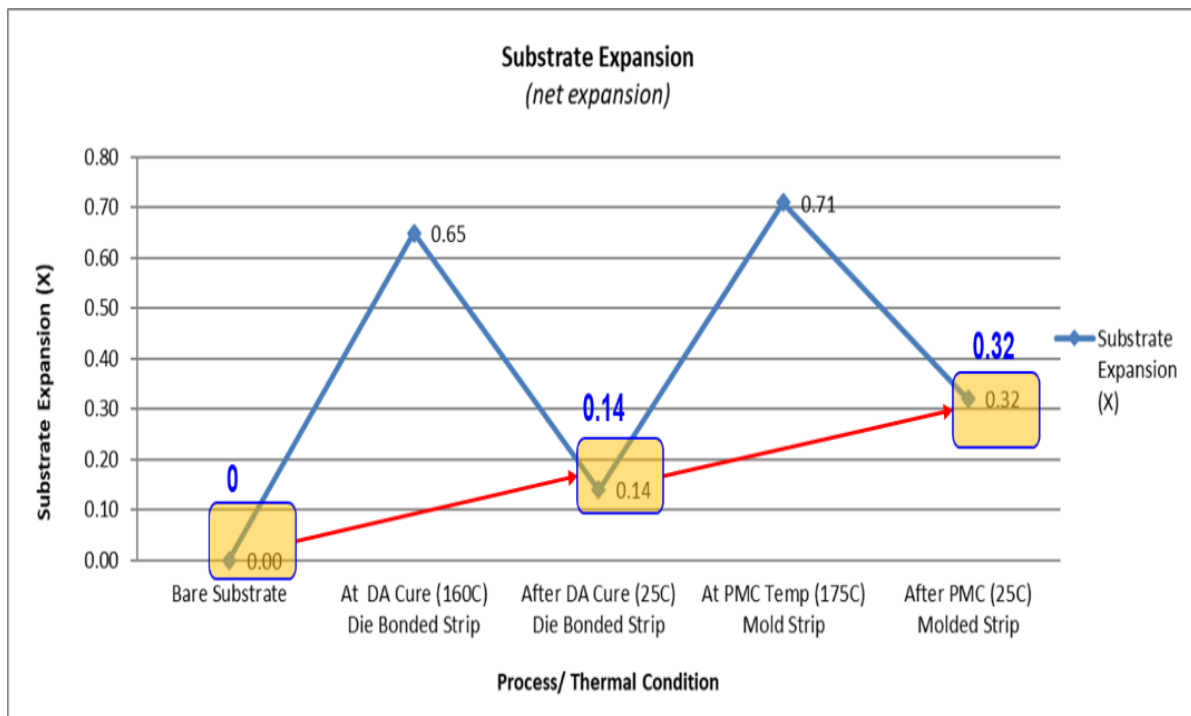
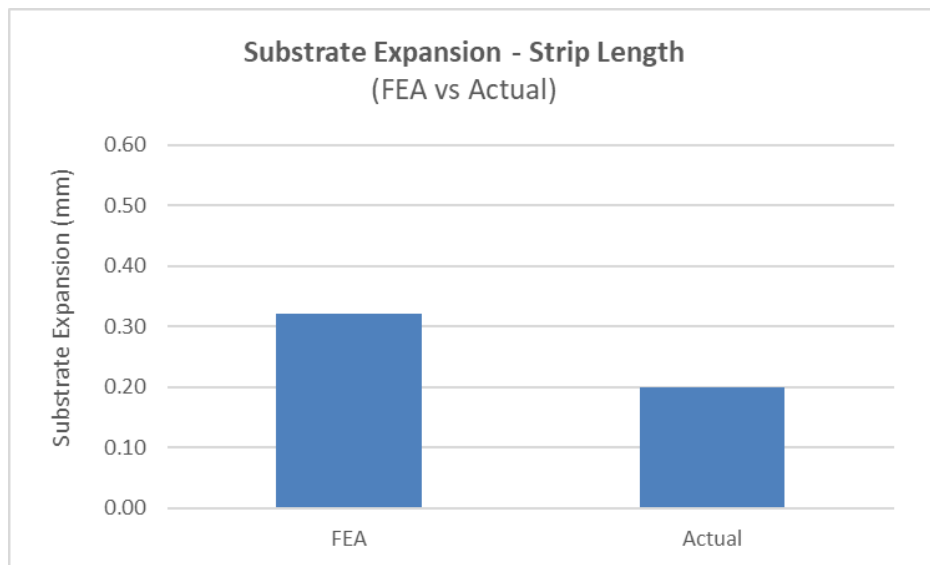**Fig. 9. Cumulative net substrate strip expansion**

Fig. 10. Molded substrate expansion comparison between FEA and actual measured value

4. CONCLUSION

Cumulative molded substrate strip expansion can be predicted using element birth and death modeling technique. As the strip passes through the different package assembly processes, the interaction among the different package components at different process temperature conditions causes a net expansion of the substrate from its original size. With finite element analysis (FEA) using the element birth and death technique, substrate expansion after each package assembly process could already be forecasted, and package assembly problems avoided by comprehending the expected expansion in the design of the toolings such as in package singulation process. Element birth and death technique is an important approach in

process-based multistep FEA simulations especially for semiconductor package assembly manufacturing. It is the modeling technique that could closely simulate the actual package assembly package manufacturing, which involve multiple process steps.

DISCLAIMER

The products used for this research are commonly and predominantly used in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because there is no intent to use these products as an avenue for any litigation but for the advancement of knowledge only. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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