



Viscoelastic Material Characterization: A Realistic Approach to Stress Analysis

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Authors' contributions

The author AZ performed the actual material characterization and author JT did the finite element warpage modeling.

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ABSTRACT

This paper presents an advanced method in materials characterization for the mold compound material in semiconductor packages to build models that can technically explain the actual warpage or stress observations under different thermal conditions and time history. In the study, the mold compound material characterization was conducted using Dynamic Mechanical Analyzer (DMA) followed by curve fitting to obtain parameters for the computer modeling input requirement. Thermo-mechanical modeling using viscoelastic material properties was conducted on a bi-material test sample model. Results showed that the new characterized viscoelastic material properties exhibited dependence on time and temperature. Slow cool down from post mold cure (PMC) to room temperature resulted in lower warpage or stress. This observed rate dependent response was explained using viscoelastic material properties in contrast to the usual linear elastic material simplification. Thus, a realistic result from stress or warpage analysis could be achieved using viscoelastic material characterization.

Keywords: *Viscoelastic materials; material characterization; stress analysis; finite element analysis; epoxy molding compound.*

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1. INTRODUCTION

Semiconductor package materials such as epoxy mold compound and substrate core are commonly used to create integrated circuit (IC) packages for different applications. Epoxy molding compound (EMC) is the encapsulation material that can provide mechanical support and protection to IC packages. In the meantime, it is also a key contributor to package warpage [1]. The viscoelastic behavior of the molding compound in fine pitch encapsulated electronic packages has a significant impact on component warpage and SMT assembly reliability [2]. Moreover, epoxy mold compound is used in leadframe-based packages such as Quad Flat No Lead (QFN) package (Fig. 1), which is the type of package being considered in this study.

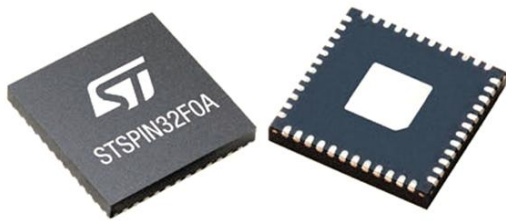


Fig. 1. QFN package using epoxy mold compound as encapsulation

During package design and development, the materials are commonly modeled using their linear elastic material properties. However, these materials are viscoelastic, which means the behavior varies with time and temperature. When using linear elastic properties for viscoelastic materials, the time-dependent behavior could not be captured such as the impact of cooling time or ramp down rate. For instance, the mold compound has properties that are highly dependent on time and temperature [3]. The amount of the warpage of the single-sided molded package (e.g. QFN) is mainly dominated by two factors. One is the difference of the coefficient of thermal expansion (CTE) between the molding compound and the substrate or leadframe, and the other is the stress relaxation due to the viscoelasticity of the molding compound [4]. There are several studies on semiconductor package warpage [5-10] that considers viscoelastic material properties.

In strip warpage analysis, the cooling time of the molded strip after PMC (post mold cure) affects

warpage. Fig. 2 shows an example of a molded leadframe strip with excessive warpage. If the mold compound is assumed to be linear elastic, strip warpage prediction would yield the same value whether the rate of cooling is fast or slow.

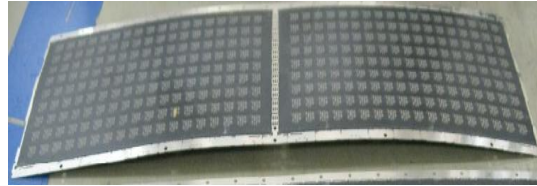


Fig. 2. QFN molded leadframe strip with excessive warpage

In linear elastic materials, it assumes a property like a spring that would just return to its original position when load is removed. The stress-strain curve is a straight line. However, in viscoelastic materials, there is permanent deformation even after load removal. The material will not return completely to its original shape or position.

As discussed by Kelly [11], the linear elastic model is used to describe a material in which the stress is proportional to the strain and returns to its original shape when the load is removed. The unloading path is the same as the loading path and there is no dependence on the rate of loading or straining. The stress-strain relationship (loading and unloading) of this linear elastic material is illustrated in Fig. 3.

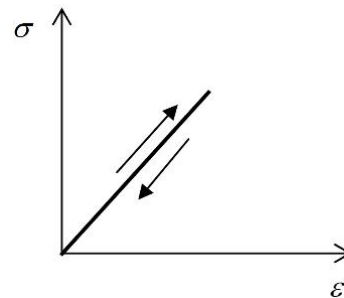


Fig. 3. Stress-strain curve of a linear elastic material [11]

The typical response of a viscoelastic material is shown in Fig. 4. The loading and unloading curves do not coincide but form a hysteresis loop. There is also a dependence on the rate of straining; the faster the stretching, the larger the stress required. The effect of the rate of stretching implies that the behavior of viscoelastic material depends on time. This

contrasts with the elastic material, whose constitutive equation is independent of time.

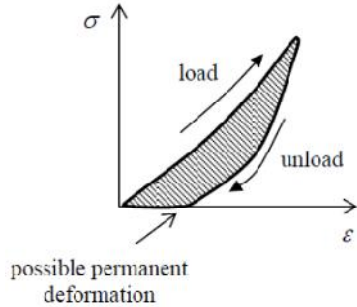


Fig. 4. Stress-strain curve of a viscoelastic material [11]

Viscoelastic material characterization is usually conducted using a DMA test. The test outputs include the storage modulus (E' or the elastic response), loss modulus (E'' or the viscous response) and tan delta, which is the ratio of the loss modulus to the storage modulus (E''/E').

Computer modeling using viscoelastic materials could be implemented in a finite element software like ANSYS using the Prony series [12]:

$$G(t) = G_0 \left[\alpha_{\infty}^G + \sum_{i=1}^{n_G} \alpha_i^G \exp\left(-\frac{t}{\tau_i^G}\right) \right] \quad (1)$$

$$K(t) = K_0 \left[\alpha_{\infty}^K + \sum_{i=1}^{n_K} \alpha_i^K \exp\left(-\frac{t}{\tau_i^K}\right) \right] \quad (2)$$

Where

G_0, K_0 = relaxation moduli at $t = 0$

n_G, n_K = number of Prony terms

α_i^G, α_i^K = relative moduli

τ_i^G, τ_i^K = relaxation time

The shear modulus G , bulk modulus K and elastic modulus E have the following well-known relationship:

$$G = \frac{E}{2(1 + \nu)} \quad (3)$$

$$K = \frac{E}{3(1 - 2\nu)} \quad (4)$$

The Williams-Landel-Ferry (WLF) equation is commonly utilized for the time-temperature

superposition intended to come up with a master curve. This is usually used to describe the time-temperature behavior of viscoelastic materials. The WLF equation has the following form [13]:

$$\log(aT) = \frac{-C1(T - Tr)}{C2 + (T - Tr)} \quad (5)$$

where T is the temperature, Tr is a reference temperature chosen to construct the master curve and $C1, C2$ are WLF constants adjusted to fit the values of the superposition parameter or WLF shift function aT .

The storage modulus and loss modulus are related to the Prony parameters by incorporating frequency, Ω , expressed as [2]:

$$G' = G_0 \left[1 - \sum_{i=1}^{n_G} \left(\alpha_i^G \frac{\alpha_i^G (\tau_i^G \Omega)^2}{1 + (\tau_i^G \Omega)^2} \right) \right], G'' = G_0 \sum_{i=1}^{n_G} \left(\frac{\alpha_i^G \tau_i^G \Omega}{1 + (\tau_i^G \Omega)^2} \right) \quad (6)$$

$$K' = K_0 \left[1 - \sum_{i=1}^{n_K} \left(\alpha_i^K \frac{\alpha_i^K (\tau_i^K \Omega)^2}{1 + (\tau_i^K \Omega)^2} \right) \right], K'' = K_0 \sum_{i=1}^{n_K} \left(\frac{\alpha_i^K \tau_i^K \Omega}{1 + (\tau_i^K \Omega)^2} \right) \quad (7)$$

2. MATERIALS AND METHODS

In this study, viscoelastic material characterization was done using DMA (Dynamic Mechanical Analyzer). A rectangular cured specimen for the mold compound material characterization was used. The test temperature range was from 30°C to 300°C with 10°C increment and a frequency sweep from 0.1 Hz to 100 Hz with 5 points per decade spaced according to a log scale.

2.1 Test Samples and Experimental Setup

The test samples used in the study were epoxy mold compound in rectangular form. The samples were prepared by molding using a customized rectangular mold. The size of the sample was 17.7 mm x 12.9 mm x 3.2 mm. Fig. 5 shows the actual epoxy molding compound test samples.

Fig. 6 shows the DMA equipment used in doing the viscoelastic materials characterization. The setup was utilizing the single cantilever clamp. The details of the setup are shown in Fig. 7. With the test sample held in a stationary clamp at one end and movable clamp at the other end, the sample was then subjected to bending or flexural loading at different frequencies and temperature. A schematic setup is illustrated in Fig. 8, which represents the actual experiment shown in Fig. 7.



Fig. 5. Mold compound test samples

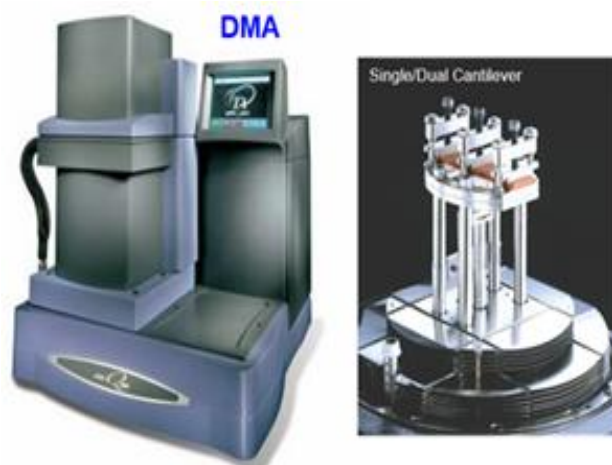


Fig. 6. Dynamic Mechanical Analyzer (DMA) used for viscoelastic materials characterization

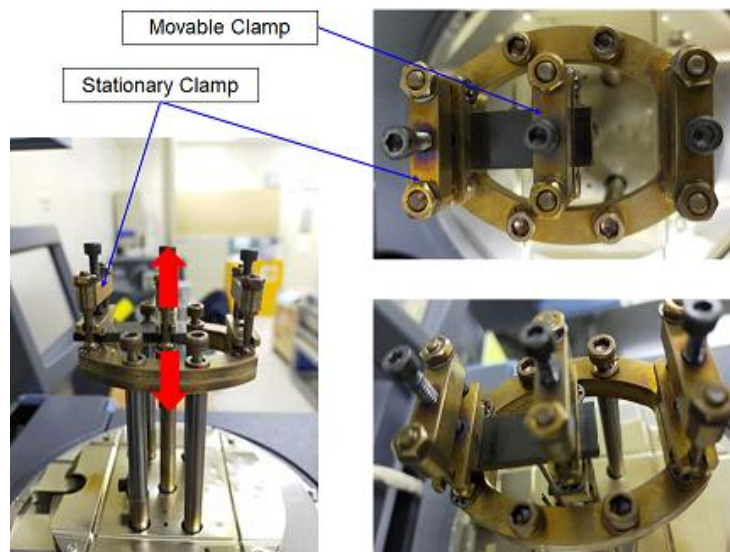


Fig. 7. Details of the experimental setup using single cantilever clamp

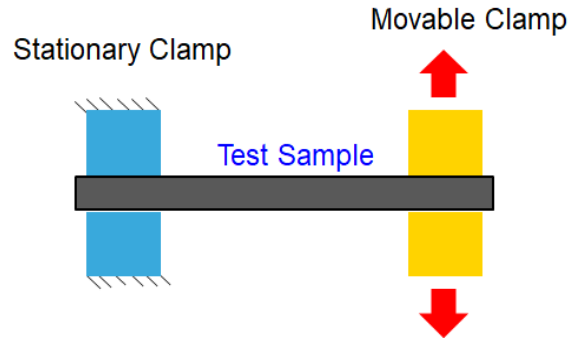


Fig. 8. Schematic of the single cantilever experimental setup

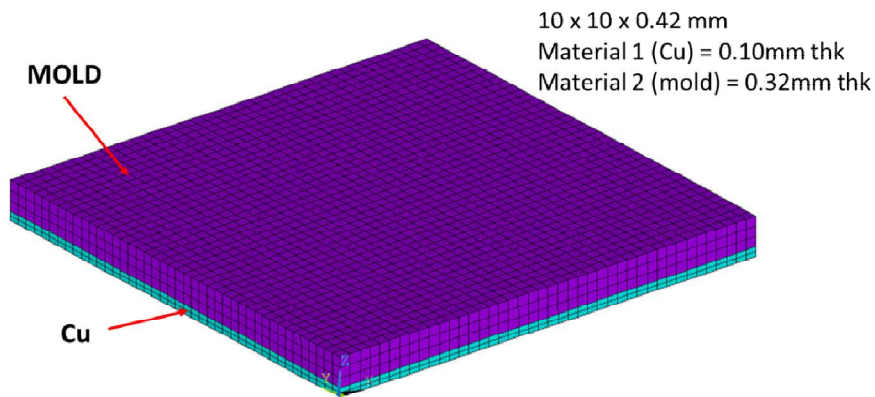


Fig. 9. Finite element model of the bi-material test sample

2.2 Mold Compound Characterization

Curve fitting (non-linear regression) using MS Excel spreadsheet was performed on the raw data obtained from DMA material testing described earlier. Regression was first done with 30 time constants using the MS Excel solver macro for the fit optimization. It was then reduced to WLF function with 15 constants suitable for ANSYS software input. The reference temperature, T_r , was arbitrarily chosen or taken from a value from similar material and C_1 , C_2 were obtained from the regression analysis. The raw data obtained at different temperatures and frequencies in the form of a storage modulus and a loss modulus were converted to the Prony parameters using equations (1) to (7).

2.3 Warpage Modeling

In the warpage modeling, viscoelastic material properties in the form of the Prony series obtained from the curve fitting were used. Two

sets of simulation were done. The first one was using the linear elastic material properties and the second one was using the time-dependent viscoelastic material properties. The finite element model is shown in Fig. 9.

3. RESULTS AND DISCUSSION

DMA output showing the relationship between the storage modulus and temperature for all the frequencies applied is shown in Fig. 10. As we can see, the modulus becomes lower at higher temperature as heat softens the mold material. Complete output results include the loss modulus and tan delta in addition to the storage modulus for each frequency (Fig. 11).

From the viscoelastic raw data results, master curves were created in MS Excel calculations. Fig. 12 shows the temperature master curve indicating reduction in modulus as temperature increases. The frequency master curve in Fig. 13 shows that at higher frequency of loading (faster loading), the modulus is also higher.

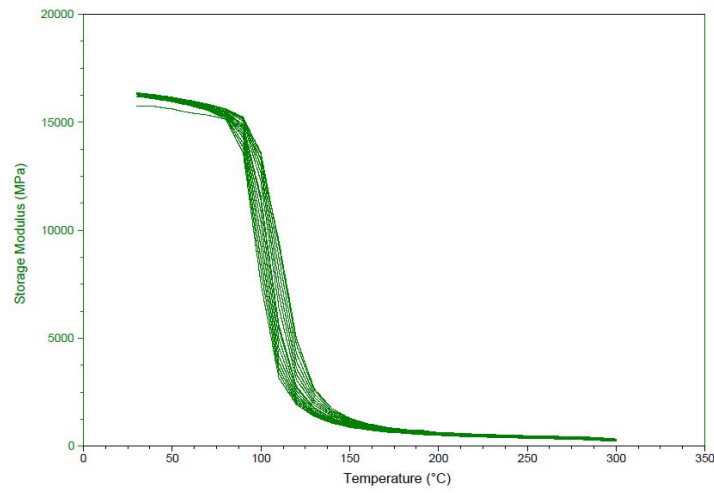


Fig. 10. Storage modulus vs temperature DMA output for the different frequencies

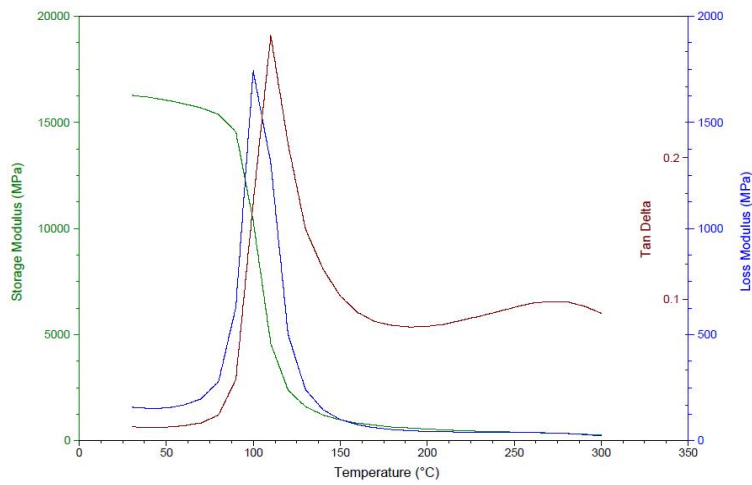


Fig. 11. DMA result showing the loss modulus, storage modulus and tan delta for 1 Hz

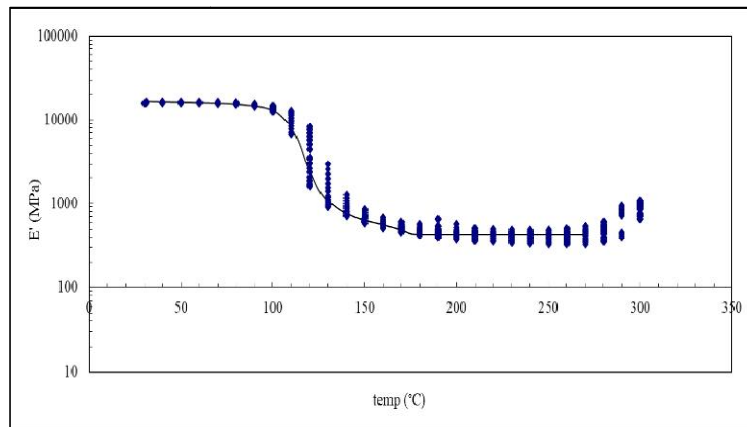


Fig. 12. Temperature master curve

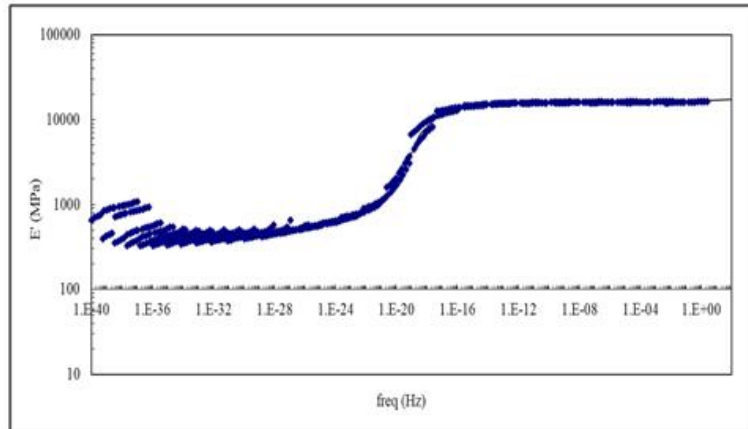


Fig. 13. Frequency master curve

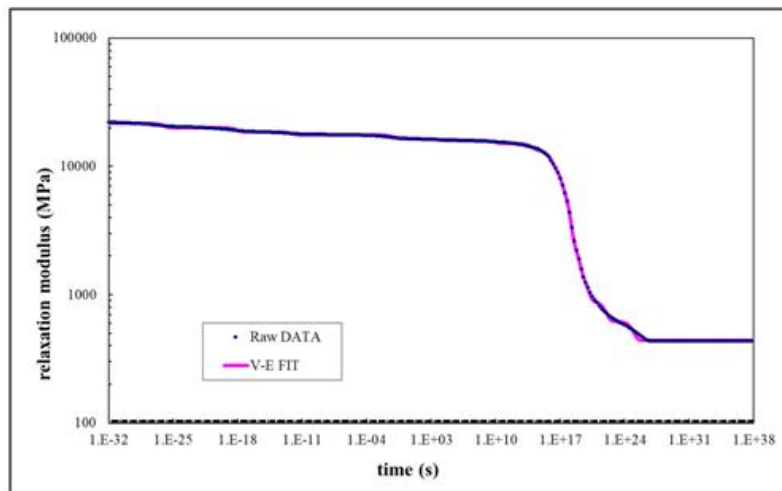


Fig. 14. Mold compound relaxation modulus vs time

Curve fitting result for the relaxation modulus of the epoxy mold compound is shown in Fig. 14, a plot of time vs modulus. It shows that for viscoelastic material, stress relaxation happens through time. This relaxation could explain why putting a weight on a stack of molded leadframe or substrate strips during PMC reduces the strip warpage.

From the modeling results, the warpage progression was plotted as shown in Fig. 15. Based on the comparison of the results, warpage prediction obtained using linear elastic material properties is higher compared to the warpage using viscoelastic material properties. This implies that using linear elastic material properties results in over-predicting the package warpage.

Warpage contour plot is shown in Fig. 16 at different thermal conditions for the viscoelastic model. Results show that the new characterized viscoelastic material properties exhibit dependence on time and temperature. Slow cool down from PMC temperature to room temperature results in lower stress or warpage. Fast cool down results in higher warpage. This time-dependent response has been successfully demonstrated using the visco-elastic material properties. For linear elastic material, modeling result is the same whether it is fast or slow cooling.

Table 1 summarizes the comparison between viscoelastic and linear elastic results. As shown, the model result of lower warpage when slow cool down is used also matches with actual observation. The results are also consistent with

those in a related study showing that the use of elastic properties of the molding compound results in an overprediction of the stresses and the strains or warpage [3]. For the linear elastic,

the model result is not in agreement with actual observation since it is not able to capture the impact of time or loading rate.

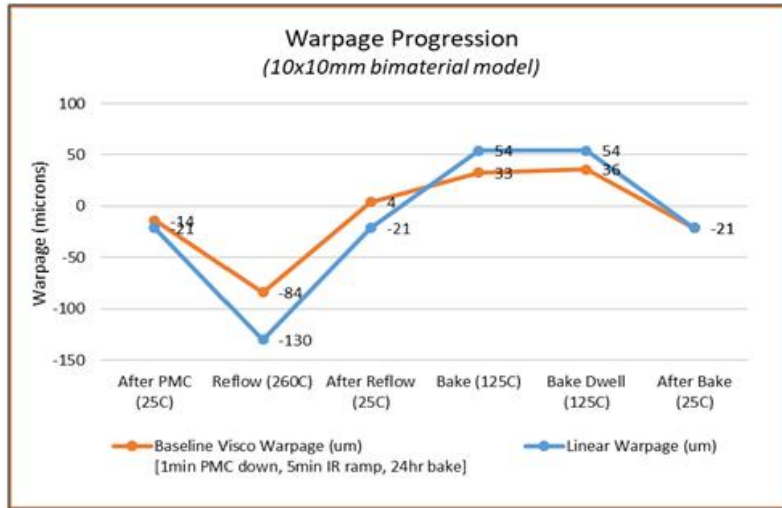


Fig. 15. Warpage progression as the package passes through the different thermal conditions (negative = “frowning” warpage; positive = “smiling” warpage)

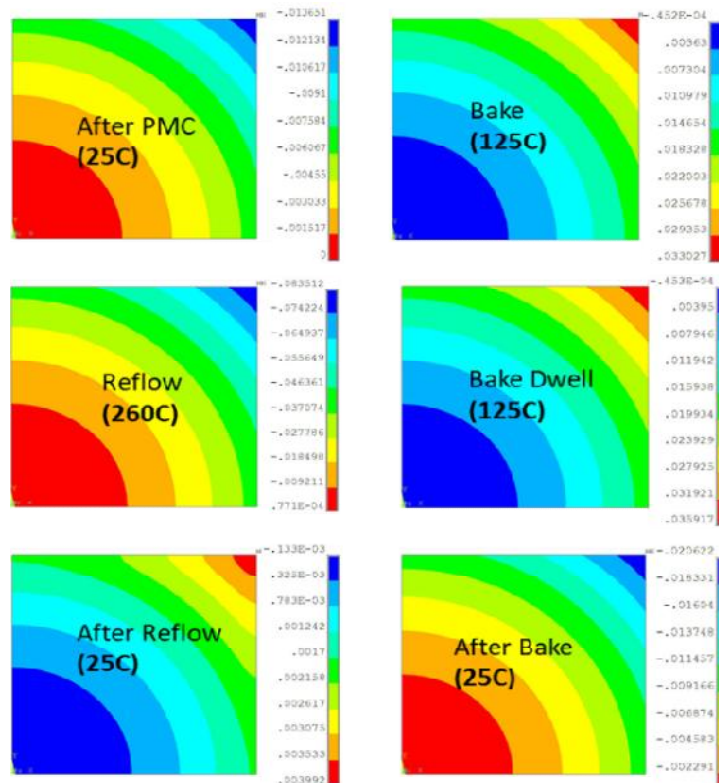


Fig. 16. Warpage contour plot results at different thermal conditions using the viscoelastic material properties. Refer to Fig. 15 for the warpage values

Table 1. Comparison of Modeling Results

Material	Warpage - Model (slow cool down vs fast cool down)	Warpage -Actual Observation (in production)
Viscoelastic	Lower Warpage	Lower Warpage
Linear Elastic	Same, overpredicted	Lower Warpage

4. CONCLUSION

In this study, it is shown that viscoelastic mold material characterization is very important to get material properties that can capture the effect of time and temperature in predicting warpage or stress and provide realistic results. Modeling using viscoelastic material properties provides results that could explain the time and temperature dependent responses observed in actual warpage measurements like the impact of slow cooling that is preferred in avoiding excessive package warpage, the use of weights during PMC and warpage reduction when strip is reworked at higher temperature. This is due to the stress relaxation effect associated with viscoelastic materials. Using the linear elastic material properties would result in over-predicting or exaggerating the warpage level and would not be realistic if absolute warpage prediction is desired. Modeling with linear elastic simplification would be useful for relative comparison only. Performing viscoelastic material characterization for mold material and other viscoelastic materials used in the package assembly needs to be considered to truly capture the correct package warpage response at different thermal conditions and loading history.

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 just for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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