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Warpage analysis of epoxy molded packages using viscoelastic based model

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Package warpage during the cooling process just after the molding is one of the critical issues in the manufacture of plastic integrated circuit (IC) packaging. Such warpage depends on the epoxy molding compound characteristics and the dimensional details of the IC package design such as downset and the chip to die-pad area ratio. In this study, the analysis methodology using a viscoelastic based material model is adopted to account the time and temperature dependent behavior of epoxy molding compound. Using such model the effect of compound thickness ratio of the top to bottom side of the package is optimized to reduce the package warpage. Secondly, the effect of the cooling rate on the warpage is also examined in this study.

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1. Introduction

Encapsulation of the wire-bonded die using epoxy molding compound (EMC) and a transfer molding process is a well-practiced method in today's Integrated Chip (IC) industry [1–3]. Trends in packaging are towards larger dies packaged in smaller and thinner packages. In the case of a thin, small outline package (TSOP) the design thickness is less than 1 mm and hence internal stress can cause external package deformation (refer Fig. 1). Such deformation can be measured using a surface roughness measurement tester or a non-contact type laser profilometer [1].

Two sources of package warpage may be present in any given sample [1, 2]. The sample may have been under-cured during molding and hence the possibilities of non-uniform cure which results in non-uniform shrinkage during the molding process. Secondly, the package design can be unbalanced from a thermo-mechanical stress standpoint, meaning that the ratio of plastic above the die and below the die-pad results in unequal force which leads to bowing upon cooling from the process temperature (around 175°C) to ambient room temperature. Thus the total stress in the package is the sum of the stress due to curing and the stress due to the thermal mismatch. The curing shrinkage depends on the chemistry of the compound while the later depends on the thermal mismatch between the various materials used within the IC chip and the package dimensions. Hence the thermal mismatch can be predicted prior and minimized during design.

Finite element method (FEM) can be applied to test variations in the package geometry, mold compound properties, lead frame materials and die attach conditions to determine their effects on the package warpage. Package design, material selection, and assembly process conditions should be selected optimally to provide minimum package warpage and minimum residual stress. Generally elastic model is used to model the polymeric behavior and thus captures only the end state of the warpage [4]. Use of viscoelastic model enables to take the process history and the glass transition effects of the molding compound and hence taken for detailed study in this paper.

2. Viscoelastic behavior of epoxy molding compound

Epoxy molding compound's stiffness behavior differs from a typical elastic material and is more close to a viscoelastic material behavior [5–8]. In simple words, these materials behave in-between the elastic solid and the Newtonian liquid, where the former undergoes a constant strain under a constant applied stress while the later undergoes a constant rate of strain under the same constant applied stress. These two material states are well represented by a spring and dashpot system in mimicking the elastic and the viscous material behaviors.

The viscoelastic material's time dependent behavior can be mathematically represented using theoretical and experimental means. These models can be constructed using springs and dashpots in series and parallel combinations. The simplest is being the maxwell element where the spring and dashpot is in series and is a better model for the stress relaxation behavior of polymeric materials [5]. The stress (σ)-strain (ε) behavior using such a model

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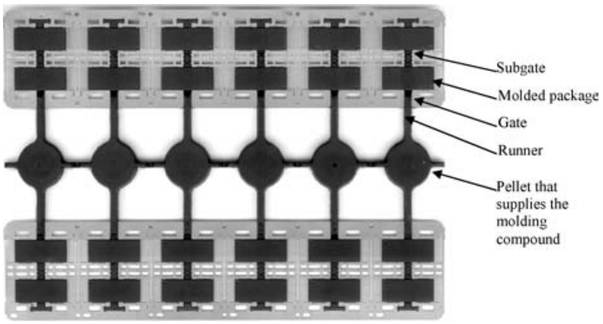


Figure 1 A typical thin small outline package that is encapsulated using epoxy molded package and molded using a transfer molding process.

can be expressed as follows:

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta} \tag{1}$$

where E is the elastic modulus and η is the viscosity. Hence the stress variation with time can be obtained in an integral form as follows:

$$\sigma(t) = \int_0^t E(t-\tau)\frac{d\varepsilon(\tau)}{d\tau}d\tau \tag{2}$$

Under a stress-relaxation condition, the time dependent elastic modulus of the maxwell element can be shown as follows:

$$E = E_\mathrm{o}\exp\left(\frac{-t}{\tau}\right) \tag{3}$$

where τ is the time constant which is the ratio of the elastic modulus and the viscosity of the material and E_o is the initial modulus. Generally polymeric material have a more complex relaxation which cannot be expressed by a single exponential curve and hence requires a more accurate mathematical model with a spectrum of Maxwell elements with different relaxation time constant τ_i ranging over a decade, as follows [6, 7]:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_\mathrm{i}e^{(-t/\tau_\mathrm{i})} \tag{4}$$

where E_∞ is the steady state value and E_i and τ_i are the individual modulus and time constant of each Maxwell elements among the 'n' such elements.

Two superposition principles can be used for the linear viscoelastic stress-strain behavior and they are the Boltzman superposition principle and the Time-Temperature equivalency principle [5–7]. The deformational behavior of viscoelastic materials to an applied stress is dependent on both temperature and time. The time factor can be seen in terms of the rate of loading, load magnitude and load duration. The temperature dependence is influenced by the thermal properties of the epoxy. In linear viscoelastic nature, the time and temperature dependence of the relationship between stress and strain is superposable and therefore essentially equivalent. The effect of time and temperature dependent viscoelastic properties can be examined experimentally by dynamic mechanical analysis which is explained in the forthcoming paragraphs.

Epoxies are thermoset in nature which means that they result in cross-linking with time as the compound cures. The rate of curing is temperature dependent and follows a arhenius relation as follows [3]:

$$\frac{dc}{dt} = (k_1 + k_2 c^m)(1-c)^n \tag{5}$$

Where,

$$k_1 = A_1 \exp(-Q_1/T) \tag{6}$$

$$k_2 = A_2 \exp(-Q_2/T) \tag{7}$$

where c is resin conversion, T is temperature in degree Kelvin, t is time and Q_1, Q_2, m and n are material constants. The cross linking process results in decrease in inter-molecular space due to the bond formation causing shrinkage in the overall dimension similar to the thermal contraction. Hence the total shrinkage strain (ε_r) is the sum of the strains viz., chemical shrinkage and thermal shrinkage as follows:

$$\varepsilon_\mathrm{T} = \varepsilon_\mathrm{c} + (\alpha_1(T_\mathrm{m} - T_\mathrm{g}) + \alpha_2(T_\mathrm{g} - T_\mathrm{a})) \tag{8}$$

where ε_c is chemical shrinkage strain, T_m is the molding process temperature, T_a is the ambient temperature, α_1 and α_2 are the thermal expansion of the compound above and below the glass transition temperature (T_g).

3. Experimental method

The dynamic mechanical analyzer (DMA) is found suitable to evaluate the viscoelastic properties of the material. The method involves in holding the EMC sample by a three point bend method and applying a sinusoidal force. This results in a bending deformation of the sample which varies sinusoidally with time. Since frequency is the inverse of time variable, the experiment can be scanned under a continuous frequency range (for e.g., 0.1 to 10 Hz). The viscoelastic effect of the EMC causes a time lag between the applied stress and resultant strain and hence the ratio of stress and strain results as a complex number. The real part is called the storage modulus and imaginary part is called the loss modulus. The storage modulus relates to the amount of recoverable energy stored within a deformed material (solid-like behavior) while the loss modulus relates to the amount of unrecoverable energy lost within a deformed material (fluid-like behavior). Measurements may be made with the sample in shear or in tension, and the sample may be subjected to a periodically varying stress or a periodically varying strain [2].

Experimentally, the material characterization of the EMC involves the determination of the relaxation data at various temperature and time (or frequency). This is obtained from a dynamic mechanical analysis (DMA) experiment and is further used in forming a master curve by rigid horizontal shifting of individual curves along the logarithmic time axis to some arbitrary reference temperature (T_r) curve. This horizontal shifting is based on Time-Temperature superposition principle, to take into account the effects of temperature and is expressed on the material's time scale by the reduced time expressed by Equation 9 [4, 6].

$$\xi(u) = \int_0^u \frac{ds}{a(T(s))} \tag{9}$$

where the function 'a' signifies the horizontal shifts for each individual curve with reference to the datum curve and is a function of temperature T, while s is a integration variable. This method is valid for the experimental curves, which join to form a smooth master curve that is illustrated in Fig. 4. If $E(T, t)$ corresponds to the relaxation curve at some temperature T, then $E_r(t) = E(T_r, t)$ is the reference curve obtained at the reference temperature T_r. According to Ferry, vertical shifting should be performed to compensate for the variation in the coefficient of thermal expansion (CTE) and is performed in terms of the density change [7]. Harper has shown that the modification of the above master curve to account for the effects of humidity can also be taken in to account in the case of polyamide material [8].

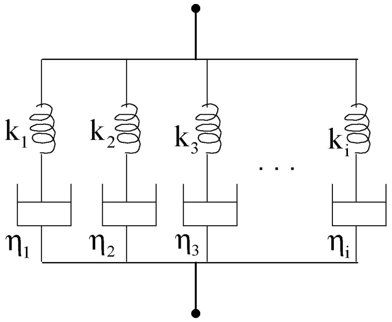


Figure 3 Assemblage of Maxwell elements to mimic the overall polymeric material's viscoelastic behavior.

Researchers have come out with various forms of horizontal shift function $a(T)$, viz., WLF model, Arrhenius and other empirical models [8–10]. Among them the WLF model (Equation 4) is the most commonly used for the

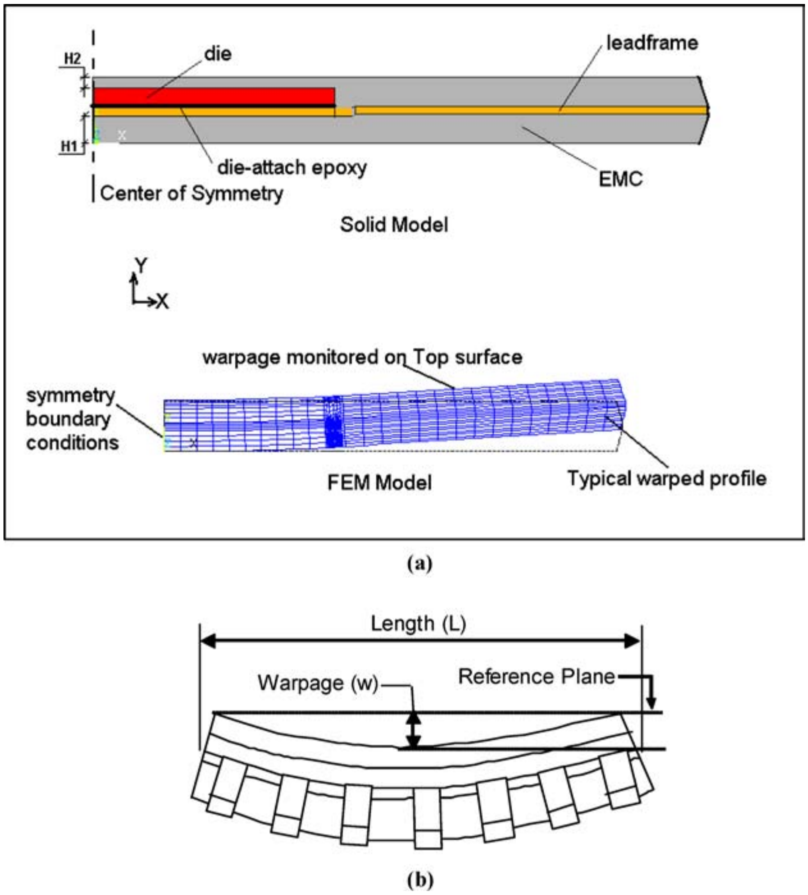


Figure 2 (a) A typical cross-section of a TSOP package and its FEM model and (b) typical warped profile and the measuring method (Semi-Standard G37-88) of the molded package.

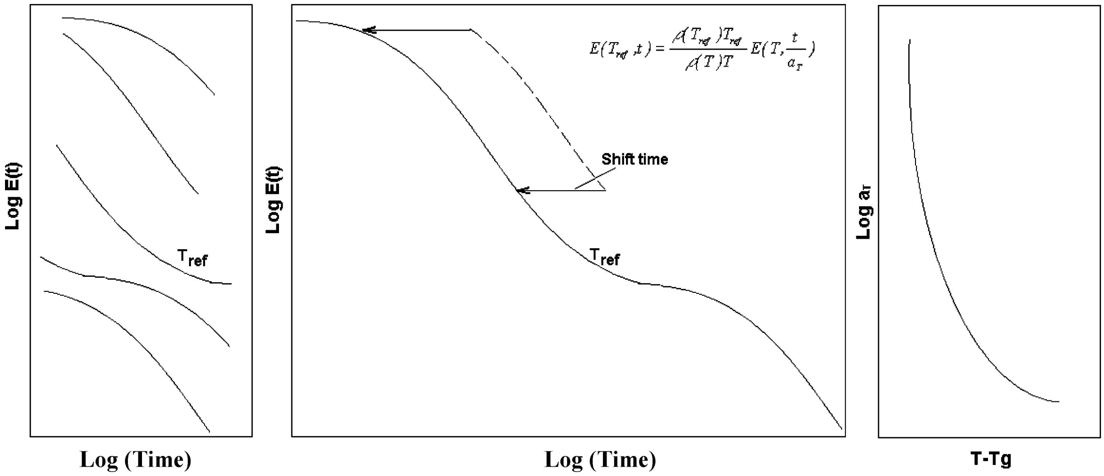


Figure 4 Typical generation of a master curve using various modulus versus time graphs obtained at different temperature that are shifted by a shift factor a_T corresponding to a reference temperature T_{ref} [7].

EMC and hence adopted for the present study. For EMCs, the constants C1 and C2 are found to be 8.86 and 101.6, respectively, while the reference temperature is maintained close to the mold temperature which is the stress free temperature, as $T_r = T_g + 45$ [9].

$$\mathrm{Log}(a(T)) = \frac{-C_1(T - T_r)}{C_2 + T - T_r} \tag{10}$$

The results from proper shifted relaxation curves give rise to a smooth fit master curve, which reflects the dependence of both temperature and time. An EMC-type of viscoelastic material displays a constant relaxation modulus after a long time, E_α, which signifies as an elastic-like behavior.

$$E(T) = E_\alpha + \Delta E^R\left(\frac{1}{a(T)}\right) \tag{11}$$

Equation 11 describes a model to determine the stress in the material at any particular temperature, (refer Fig. 4). Among the various curve-fitting techniques, the Prony Series form [7, 11] for the relaxation modulus is commonly used for most finite element packages as shown earlier in Equation 4 using 'N' Maxwell elements (see Fig. 3) as follows:

$$\Delta E^R(t) = \sum_{i=1}^{N} E_i e^{-t/\tau_i} \tag{12}$$

4. FEM model details

Among the various numerical techniques, Finite Element Method is the most widely used simulation technique for analyzing the thermo-mechanical behavior of electronic packages during their manufacture and usage. Plastic encapsulated IC packages are a composite structure (refer Fig. 2), with at least four different materials to be considered in the analysis viz., die-attach epoxy, silicon, leadframe and the EMC.

Two-dimensional finite element analysis using isoparameteric quadrilateral elements was used to model the IC and ABAQUS$^{\mathrm{TM}}$ was used in the solution and post-processing. Perfect interfacial adhesion was assumed between the various components of the IC. The material properties assumed for the various components are listed in Table I. The three EMCs had different chemical formulation with different filler percentage viz., 84%, 82% and 82%, respectively and hence they exhibited different glass transition temperature viz., 125, 135 and 150°C, respectively. Fig. 5 show the variation of thermal expansion and modulus with temperature, and the variation of cure shrinkage strain for the three different EMCs. In the present study, the viscoelastic material behavior of the EMC was mimicked using 14 Maxwell elements (see Fig. 3). Fig. 6 shows the modulus and time constants of these Maxwell elements that portray the master curves for the three different EMCs used in the analysis.

In the present study, the analysis is aimed at determining the package warpage for different downset dimensions, in other words the ratio of the EMC thickness on the bottom of the die (H1) to the EMC thickness on the top of the die (H2) as shown in Fig. 1. The analysis was repeated for different cooling profiles, expressed in Equation 13, from the initial molding temperature of 175°C to the ambient temperature, as shown in Fig. 7. By varying the time

TABLE I Material properties used in the FE analysis

Material	Young's modulus (GPa)	Poisson's ratio	CTE (ppm/°C)
Silicon die	131	0.24	2.3
Leadframe (Alloy 42)	119	0.33	17
Die attach epoxy	0.36	0.4	37

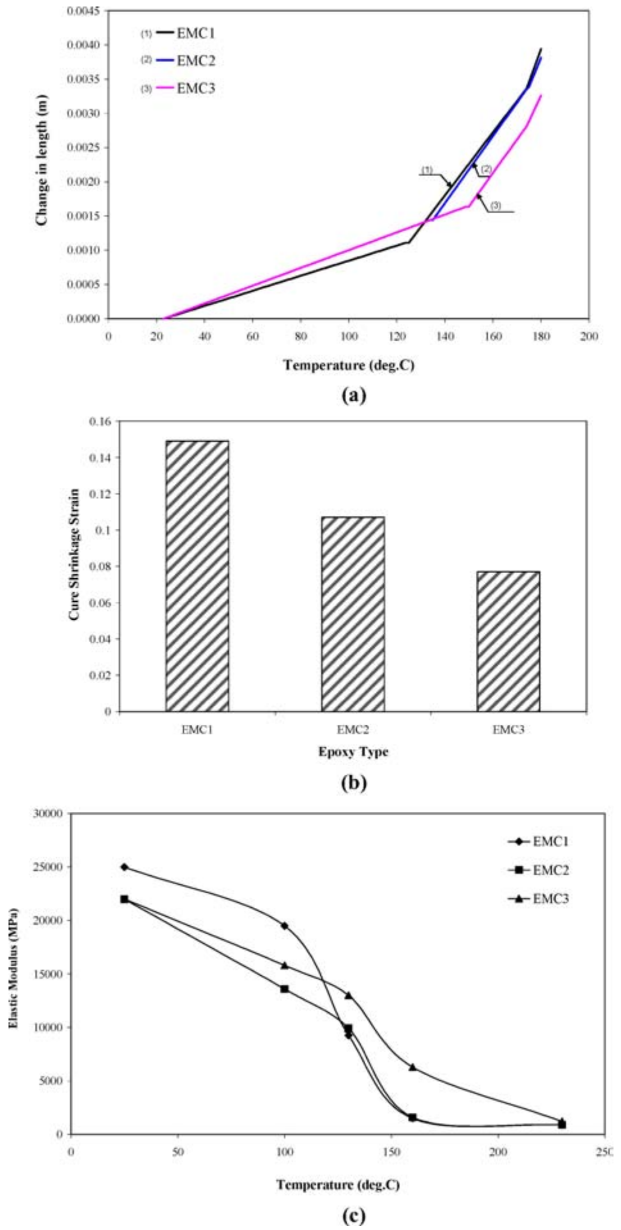


Figure 5 Variation of thermo-mechanical properties of the three different EMCs (a) thermal expansion coefficient with temperature, (b) cure shrinkage strain and (c) elastic modulus with temperature for the three different EMCs.

decay constant T_d, the cooling rate can be adjusted [11]. The constant T_o corresponds to the ambient temperature.

$$T = T_o + T \exp\left(\frac{-t}{T_d}\right) \quad (13)$$

5. Results and discussion

Finite Element Method (FEM) is a viable method to account and analyze the time and temperature dependent property variation of polymeric materials such as epoxy molding compounds. Secondly, it has the distinct advantage to model more closely to the exact geometry. Thirdly, it has the advantage to model the various material properties in the geometry as well as the anisotropy of the individual phases. Finally, it can model the exact fixity and the load conditions on the specimen.

In the present study, the package warpage was defined as the out-of-plane displacement between the package corner and the center of the molded package's top surface. The percent of warpage or warp factor was defined as the ratio of the warpage and the side length of the package. Fig. 2b shows a typical deformation pattern of a warped package.

5.1. Effect of thickness ratio on overall package warpage

Fig. 8 shows the variation in the warped profile with change in the thickness ratio of the plastic on the top and bottom side of the package. Table II lists the variation in warpage magnitude with change in thickness ratio. It is clear that an optimum thickness ratio exists for a particular package dimension (viz., package size, leadframe downset, die size, etc.) and material type (EMC, die-attach, etc.) that results in minimal package warpage which can fit with in the specification. For the present chosen package dimension, minimum warpage results when the H1/H2 ratio is 1.22.

5.2. Effect of EMC selection

A similar study with the three different EMCs was conducted for different thickness ratios. Fig. 9 shows the warped profile for a thickness ratio of 1.0, from which it is clear that the warpage magnitude depends on the EMC's material characteristics chosen for the package. Based on the present study, EMC-3 provides the mimimal warpage under similar package dimension and process condition. This is mainly due to its minimal cure shrinkage compared to other epoxies shown in Fig. 5b and lesser thermal expansion mismatch (see Fig. 5a) with respect to the leadframe and silicon die.

5.3. Effect of cooling rate

Analysis was also performed for three different cooling rates, shown in Fig. 10a, to study the effect of cooling rate on the final warpage profile. In reality, convective cooling takes place on the package outer surface with a heat transfer coefficient of 5–8 W/m^2 K, hence packages exhibit a cooling profile, close to $Td = 50$ as shown in Fig. 7. But warpage results in Fig. 10b shows that the effect of cooling rate variation to some extent does not affect the overall package deformation at the final steady state. In practice, since molded strips are placed one above

TABLE II Warpage percentage variation with thickness ratio

Thickness ratio	0.67	0.82	1.0	1.22	1.5
Warpage (%)	4.86	3.19	2.26	0.71	0.76

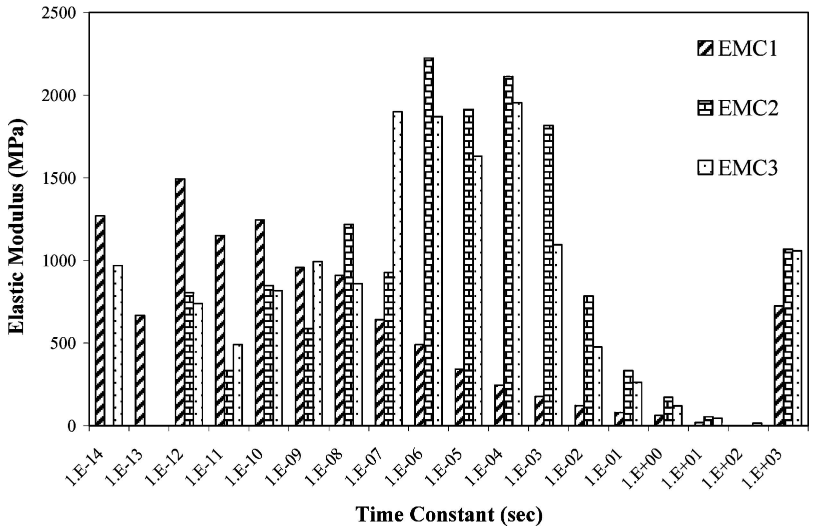


Figure 6 Elastic modulus amplitude (E_i) versus time constant that characterizes the master curves for the three different EMCs used in this study.

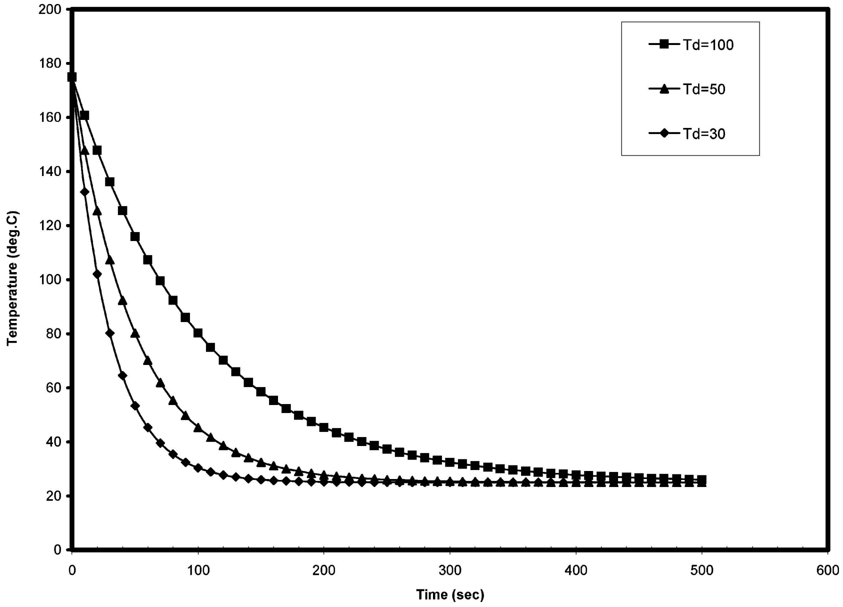


Figure 7 Three different cooling curves analyzed in the analysis.

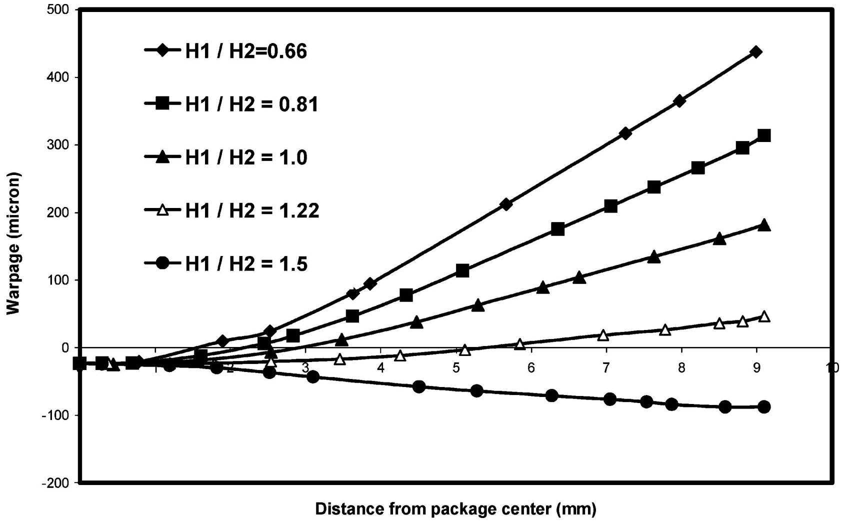


Figure 8 Warpage profile of TSOP package (using EMC1 and T_d=50).

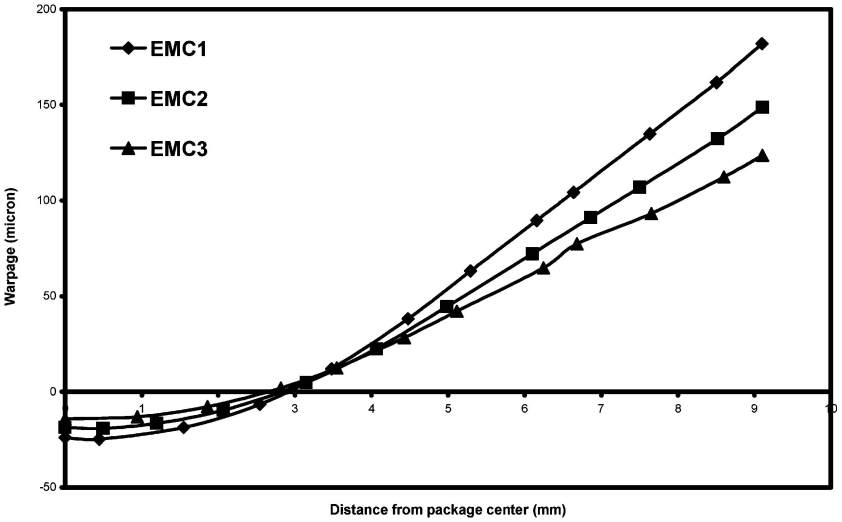
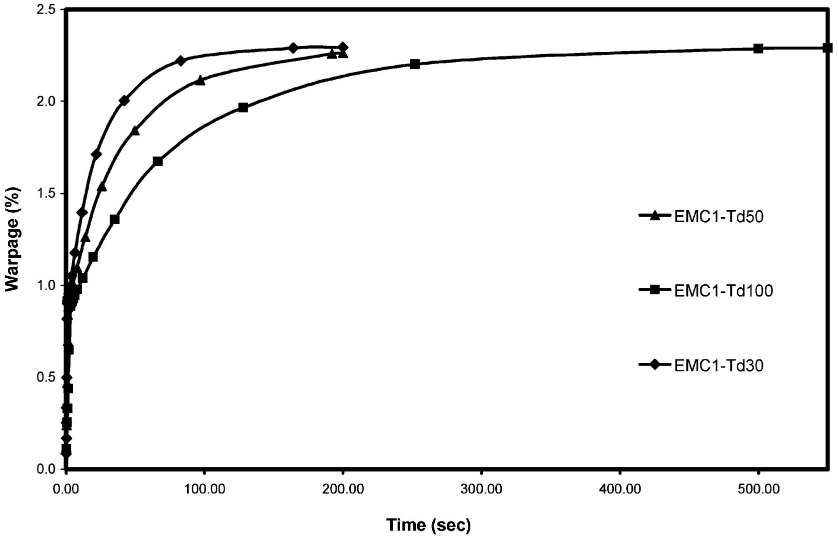
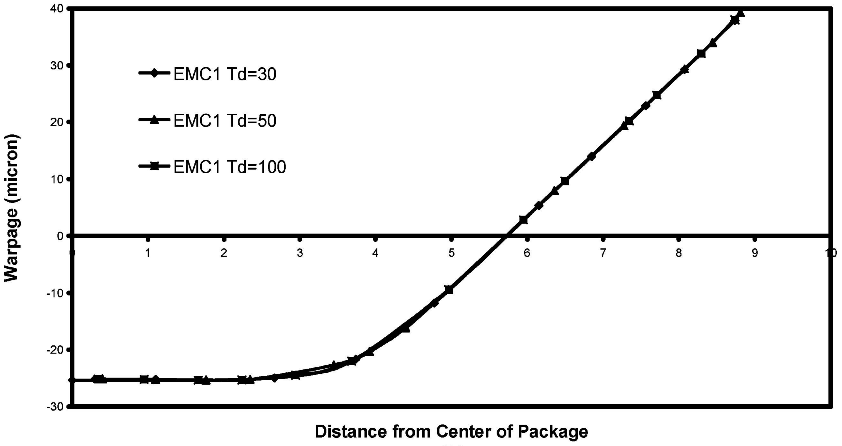


Figure 9 Warpage profile for different EMC characteristics (H1/H2 = 1, $T_d = 50$).



(a)



(b)

Figure 10 Package warpage of TSOP with H1/H2 = 1, EMC1 and under different cooling rates: (a) warpage variation with respect to time, (b) steady state values of the warpage.

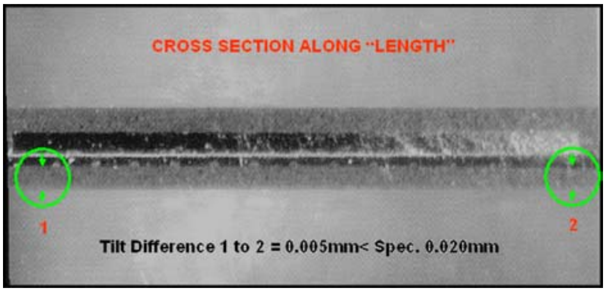


Figure 11 Cross Section of the molded TSOP package showing minimal warpage and die pad tilt of only 5 microns.

the other in magazine holder, the cooling rate at the bottom is lower than the top surface due to the presence of molded strips at the bottom. Hence their curing rate is expected to vary. This can cause variation in the warpage development in the package. Hence further work is in progress to take these factors into detailed study.

5.4. Experimental validation

In the present study, based on the results shown in Fig. 8, leadframes and molds were designed to provide a downset such that it results in an epoxy thickness ratio (H1/H2) of 1.2 in the final package. Based on Fig. 9, EMC-3 was chosen as the encapsulant for the final trial to minimize the final warpage magnitude. The package size corresponds to a thin small outline package with a dimension of 18 mm length, 4 mm length and 0.9 mm thick. Warpage measurement were made on 25 samples and results showed that the average warpage on top and bottom side of the package were found to be $25 \pm 4\ \mu$m and $22 \pm 5\ \mu$m, respectively, which are well within 0.13% of the overall length. The results were further confirmed by proper cross-sectioning the molded packages, as shown in Fig. 11, which clearly shows that the warpage profile and die-pad tilt magnitudes, are well within the design limit.

Generally in an elastic analysis, the history of the material's property change is not taken into account. It computes the deformation and stress using the end state of the material's property which is at the room temperature condition. While in the present study, the viscoelastic model of the elastic modulus along with temperature variation of the thermal expansion (CTE) has been taken into account. Such an updated model provides more accurate prediction of the warpage. In the present study, the elastic analysis was seen to predict the warpage of only 33% compared to a viscoelastic model prediction.

Thus in summary, FEM based simulations can be used effectively as an aid to account the viscoelastic effects in the area of package design. If the same package outline dimension is used with different die sizes, the analysis would be able to predict the effect of die to die-pad area ratio on the warpage profile. Further, the simulation can be used to minimize the warp profile by determining the optimum design parameters such as thickness ratio of the epoxy placed on the top and bottom of the die, proper EMC material characteristics and manufacturing process conditions, such as cooling profile of the IC from mold temperature to ambient temperature. Further, further work is in progress using a three-dimensional analysis which takes non-linear viscoelastic analysis model. Nevertheless the present outlined simplistic model helps to minimize warpage which enhances the downstream processes such as trim and form process and lazer marking process in a semiconductor packaging environment.

6. Conclusion

Based on the present study following conclusions can be arrived:

1. The art of incorporating the viscoelastic formulation in FEM modeling of epoxy molding compound has been well proven.
2. Viscoelastic based FEM simulation has effectively predicted the package dimension to minimize the warpage to reduce the design lead time.
3. Among three different EMCs, the molding compound with higher T_g, smaller cure shrinkage and lower thermal mismatch with the leadframe results in minimal warpage.

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