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Modeling of Molded Electronic Package Warpage Characteristic with Cure Induced Shrinkage and Viscoelasticity Properties

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iNEMI

IEEE ELECTRONICS PACKAGING SOCIETY

iNEMI: Warpage Characteristics of Organic Packages, Phase 4

iNEMI Technology Roadmap 2013

- Identify package warpage as key challenge

Phase 1 (2011-13)

- Literature survey
- Establish metrology correlation between sites and increase awareness
- Reaching out to industry for component donation
- (Forming & Storming)

Phase 2 (2013-2014)

- Establish current technology package dynamic warpage (POP, PBGA, FCBGA)
- Measurement protocol (effect of "As Is", "Bake" and Moisture Exposure Time (MET)) and sample size needed.
- (Norming)

Phase 3 (2015-2016)

- Continue establishing technology package dynamic warpage (all kind)
- Dynamic warpage measurement metrology assessment.
- (Performing)

Phase 4 (2016-2017)

- Continue establishing technology package dynamic warpage of new package technology (all kinds)
- Leverage previous effort to study the impact of Low Temperature Solder on dynamic warpage requirement
- Collaborate with simulation software to derive modeling approach in better predict the dynamic warpage

Continuous focus on dynamic warpage characteristic of latest packaging technology and warpage measurement metrology

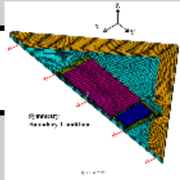
Project Scopes in Phase 4 SOW

Characterization of latest packaging technology

- Characterize emerging electronic packaging technology dynamic warpage behavior to develop a better understanding of the current development of package construction and material development as listed in Table I.
  - Silicon Interposer and Embedded Silicon Bridge with different package stiffeners and constructions for Heterogeneous Packaging Solution
  - Next generation of POP packages that leverages wafer level process for package construction which include Panel and Wafer level molding. These also include the use of new fiber reinforced mold material for warpage control.
  - System In Package/Multi Chip Package (BGA) with different configuration and layout.
  - Embedded Package (embedded silicon, actives and passives)

Assess the impact of Low Temperature Solder (LTS) on package dynamic warpage requirement

- To assess the impact of lower temperature solder on package warpage for those packages collected in Phase 2 and 3.
- To establish the risk level based on package technology with respect to warpage only.



Assessment the use FEA in optimizing package warpage

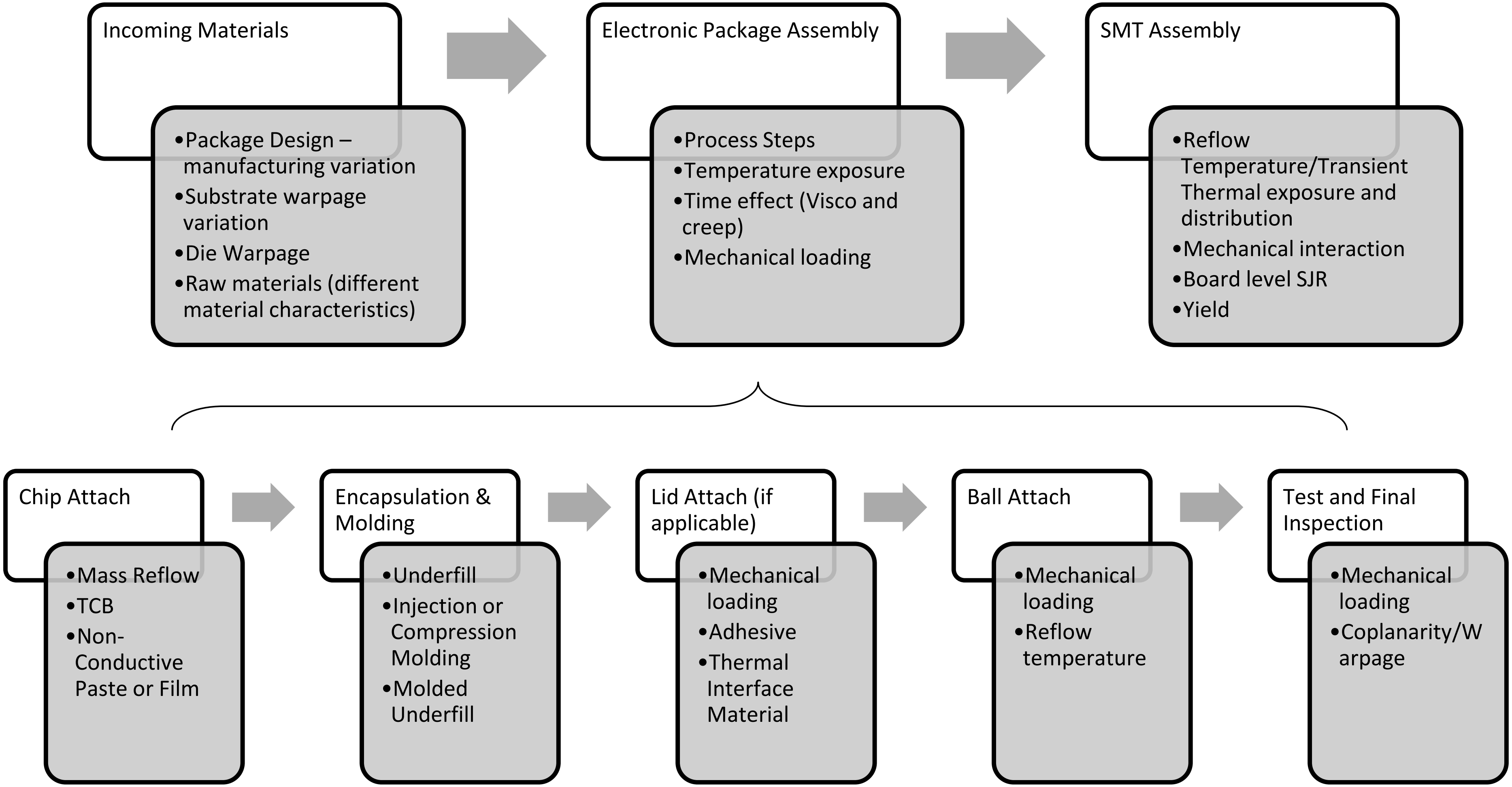
- Establish modeling optimization approach and tools requirement to enable higher accuracy prediction technique
- Compare modeling with experiment data and identify potential gaps for further development in FEA technique

Content

- Background and motivation
- Modeling approach and governing equations
- Sensitivity Studies
- Summary

Disclaimer: The work here covers some feasibility study which collaborated with iNEMI and we are not endorsing any software in particular.

Multi-physics in Assembly Process



Incoming Materials
- Package Design – manufacturing variation
- Substrate warpage variation
- Die Warpage
- Raw materials (different material characteristics)

Electronic Package Assembly
- Process Steps
- Temperature exposure
- Time effect (Visco and creep)
- Mechanical loading

SMT Assembly
- Reflow Temperature/Transient Thermal exposure and distribution
- Mechanical interaction
- Board level SJR
- Yield

Chip Attach
- Mass Reflow
- TCB
- Non-Conductive Paste or Film

Encapsulation & Molding
- Underfill
- Injection or Compression Molding
- Molded Underfill

Lid Attach (if applicable)
- Mechanical loading
- Adhesive
- Thermal Interface Material

Ball Attach
- Mechanical loading
- Reflow temperature

Test and Final Inspection
- Mechanical loading
- Coplanarity/Warpage

Current Modeling Approach is it Adequate?

Create FEA Geometry, Meshing and apply constraint boundaries condition

and include incoming variations

Apply linear and visco-elasticity material constitutive properties and include different processing steps of how materials are added to the construction of the package

Compute the model from the initial stress free condition

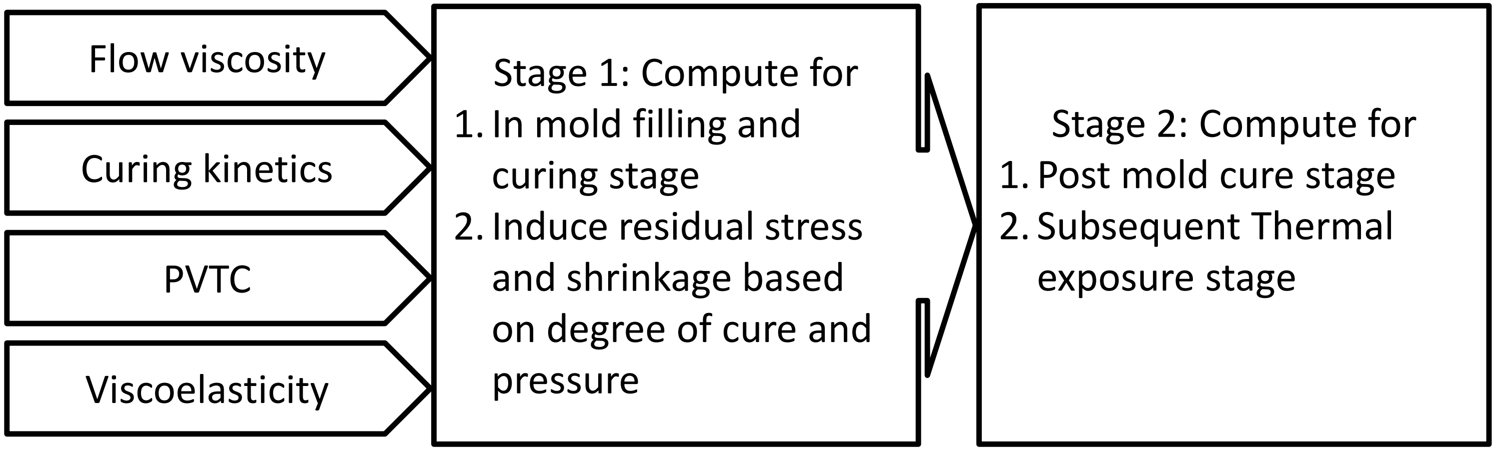
How to account for the individual residual stresses of the components during assembly

Post processing to extract predicted package warpage for risk assessment with account for process, material and incoming variation.

Significant effort needed to account for multi-physics interaction in packaging assembly for warpage prediction

Many commercial available modeling tools are still working to refine the modeling needs.

Moldex3D



Flow viscosity

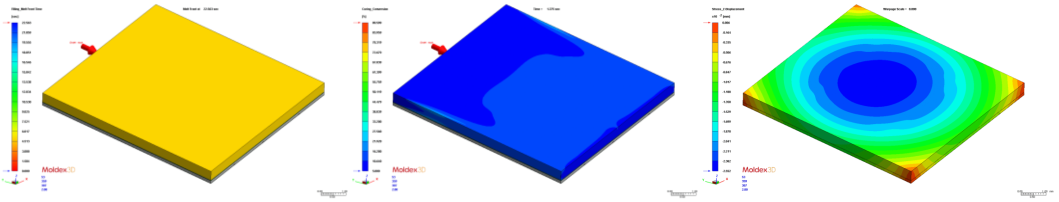
Curing kinetics

PVTC

Viscoelasticity

Stage 1: Compute for
1. In mold filling and curing stage
2. Induce residual stress and shrinkage based on degree of cure and pressure

Stage 2: Compute for
1. Post mold cure stage
2. Subsequent Thermal exposure stage



Filling

Curing

Post mold cure deformation

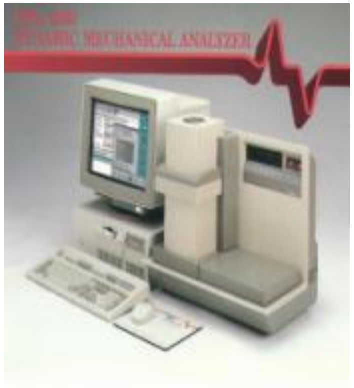
Coupled mold flow, curing kinetics, visco-elasticity and shrinkage and conjugate heat transfer in one environment

Material Characterization in Moldex3D Laboratory

MCR 502
Rotation and oscillation tests for viscoelastic properties

TMA 4000
Coefficient of thermal expansion

DSC 8500
Transition temperatures and crystallization kinetics

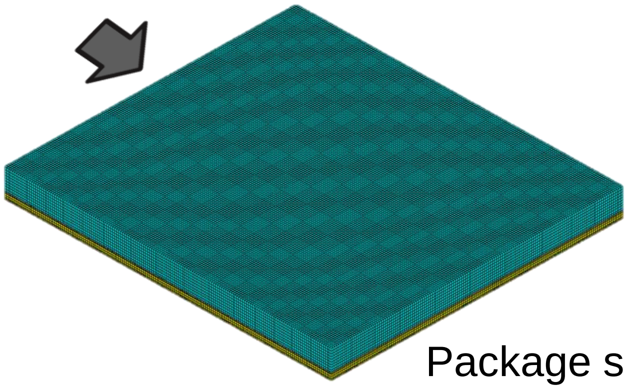


DMA 2690
Dynamics mechanism analysis for relaxation modulus

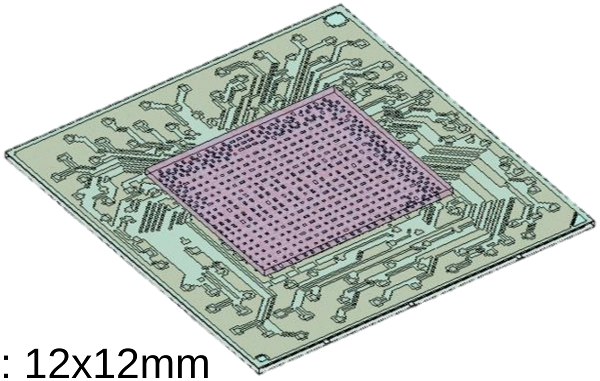
PT-6800
Specific volume with curing (PVTC)

H5DR
Thermal conductivity

Test Model for Demonstration



Mold flow direction



Package size: 12x12mm
Package thickness: 0.61mm
Mold thickness: 0.45mm

Materials	Modulus (MPa)	CTE (ppm)
Silicon	172800	3
Substrate	18190	14.4
Copper	110000	17
Dielectric	13170	6.3
Mold	Viscoelasticity	PVTC

Mold Flow Governing Equations

Mass balance

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0$$

Momentum balance

$$\rho\frac{D\mathbf{u}}{Dt}=\nabla\cdot\boldsymbol{\tau}-\nabla p+\rho g$$

Energy balance

$$\rho C_p\left(\frac{\partial T}{\partial t}+\mathbf{u}\cdot\nabla T\right)=\nabla\cdot k\nabla T-\tau:\dot{\gamma}+S$$

Thermoset conversion balance

$$\frac{d\alpha}{dt}=(k_1+k_2\alpha^m)(1-\alpha)^n$$

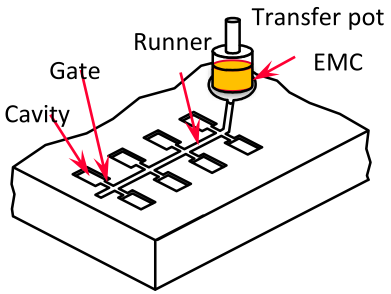
Density, ρ

Relationship between $\boldsymbol{\tau}$ and $\mathbf{u}$ or viscosity, η

Heat capacity, C_p

Thermal conductivity, k

Conversion rate, α



CAE procedure

⇩

Flow/Cure behavior

⇩

Post mold cure analysis

Temperature-pressure-cure dependent volume, $V(T, P, C)$

Relaxation Modulus, G

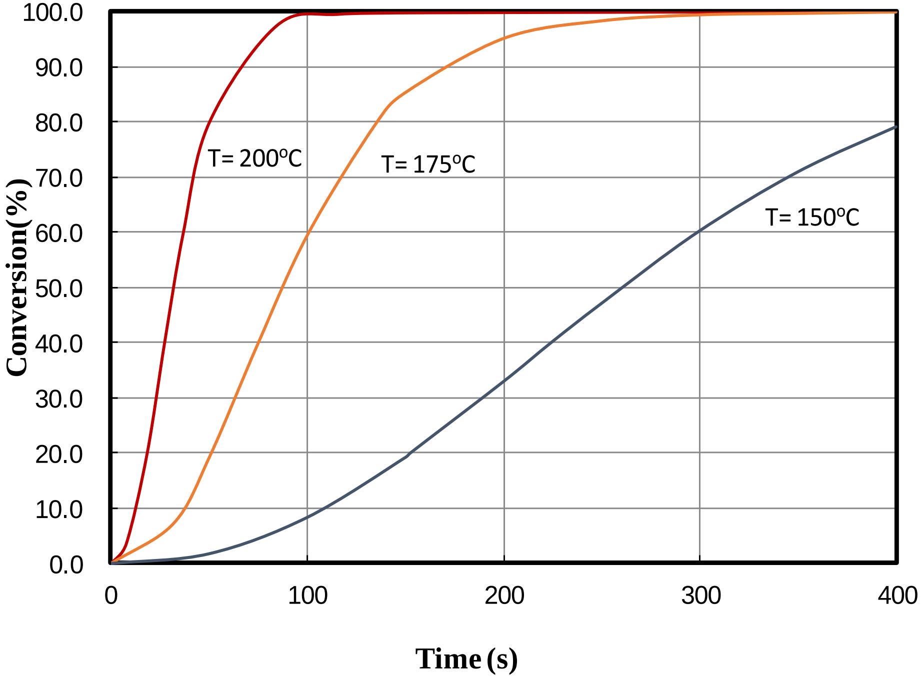
Curing Kinetics Mold Material Properties

The combined model to investigate the curing kinetics of the given mold because of its ability to accurately predict the experimental data. The combined model can be expressed as follows:

$$\frac{d\alpha}{dt} = \left(k_1 + k_2\alpha^m\right)\left(1-\alpha\right)^n$$

$$k_1 = A_1 \exp\left(-\frac{E_1}{RT}\right)$$

$$k_2 = A_2 \exp\left(-\frac{E_2}{RT}\right)$$

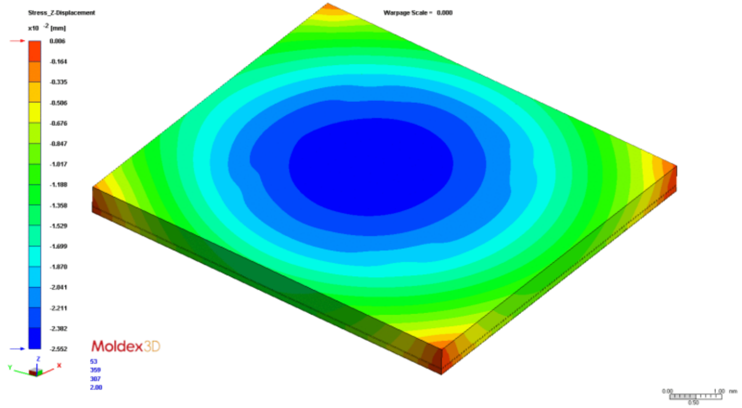


Structural Stress Governing Equations

Stress balance

$$\nabla \cdot \boldsymbol{\sigma}(t) = 0,$$

$$\sigma = \mathbf{C}(\varepsilon - \varepsilon^{PVTC}), \varepsilon = \frac{1}{2}(\nabla \mathbf{U} + \nabla \mathbf{U}^T)$$



Compute for thermal and cure induced strains can be expressed in the following PVTC equation for epoxy:

$$\varepsilon^{PVTC} = VS(P, V, T, C)$$

PVTC Mold Material Properties

The two domain modified Tait model is used to formulate the specified volume of resin as below:

$$\frac{1}{V}=\frac{1}{V_{uncured}}(1-\alpha)+\frac{1}{V_{cured}}\alpha$$

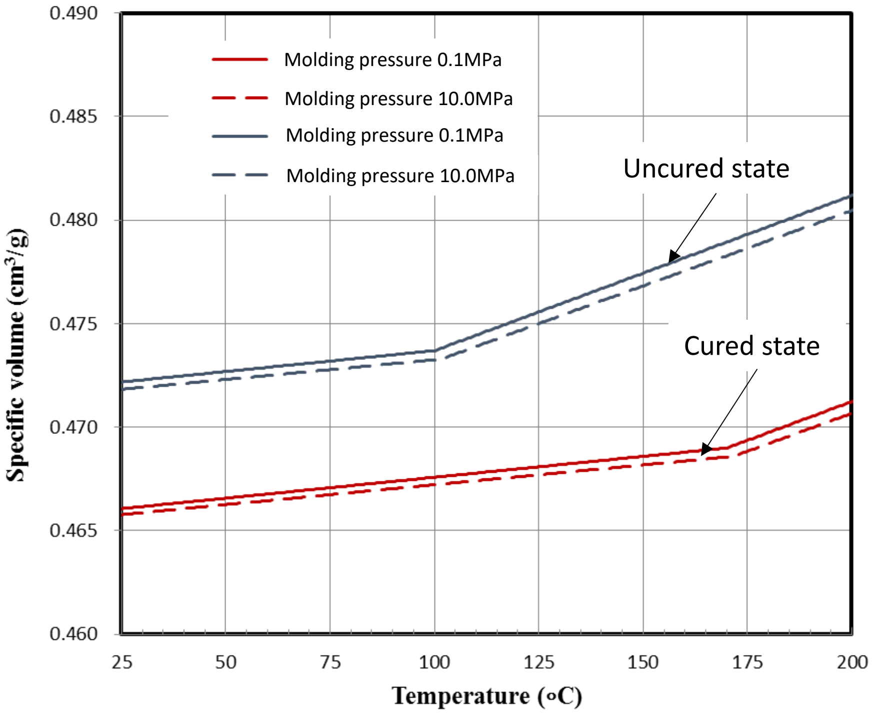
$$V_{cured/uncured}=V_0\left[1-C\ln\left(1+\frac{p}{B}\right)\right]$$

$$V_0=\begin{cases} b_{1S}+b_{2S}\overline{T}\ , \text{ if } T\le T_t \\ b_{1L}+b_{2L}\overline{T}, \text{ if } T>T_t \end{cases}$$

$$B=\begin{cases} b_{3S}\exp\left(-b_{4S}\overline{T}\right), \text{ if } T\le T_t \\ b_{3L}\exp\left(-b_{4L}\overline{T}\right), \text{ if } T>T_t \end{cases}$$

$$T_t=b_5+b_6P$$

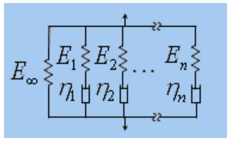
$$\overline{T}=T-b_5, C=0.0894$$



Viscoelasticity Governing Equations

- **C** is a tensor and function of relaxation modulus E(*t, T,*) curve:

$$\mathbf{C} = C_{ijkl} = \frac{E(t)}{2(1+\nu)}\left(\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk}\right)+\frac{\nu E(t)}{(1+\nu)(1-2\nu)}\delta_{ij}\delta_{kl}$$



- Relaxation stiffness in VE analysis:

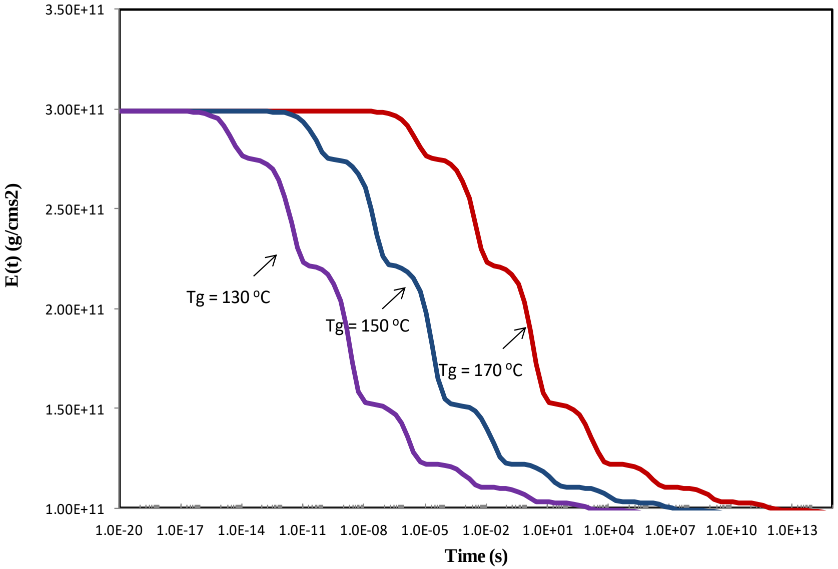
$$E(T,C,t)=E(T_{ref},C_{ref},t/a)$$

  - where the temperature and curing shift factor

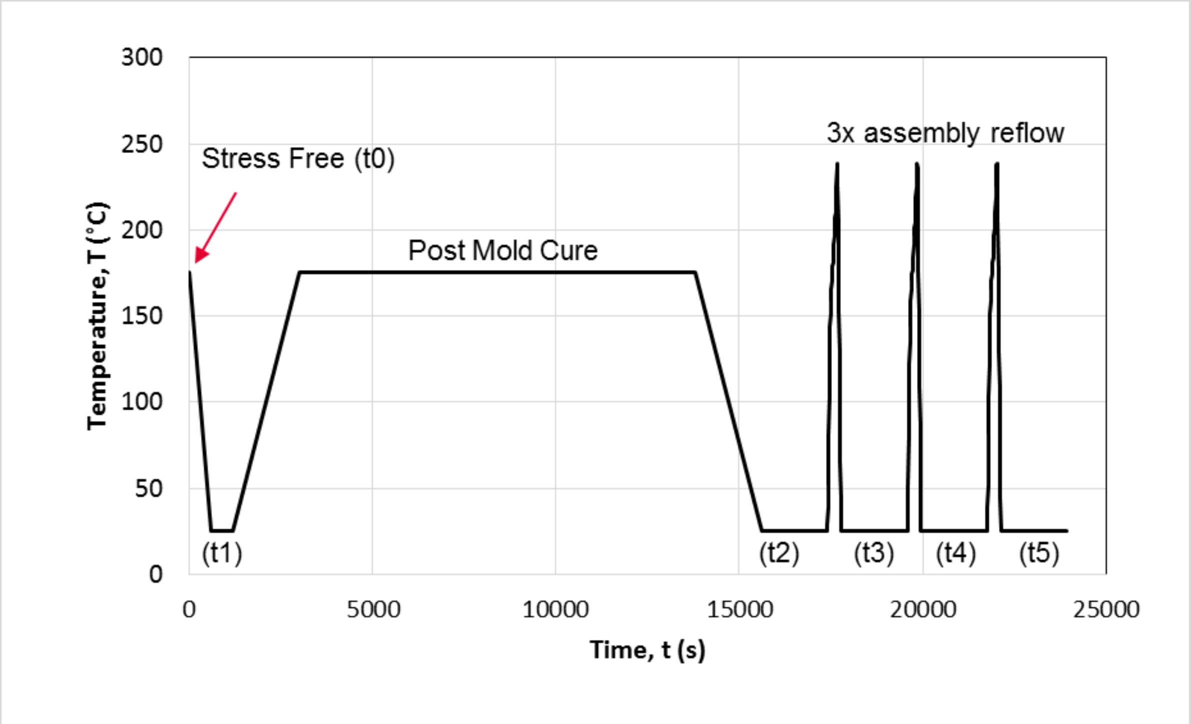
$$\log a_T = \frac{-C_1(T-T_{ref})}{C_2+T-T_{ref}}$$

$$\log a_C = a_1C^n + a_2C^{(n-1)}+\ldots+a_0$$

Viscoelasticity of Mold Materials



Loading Boundaries Condition



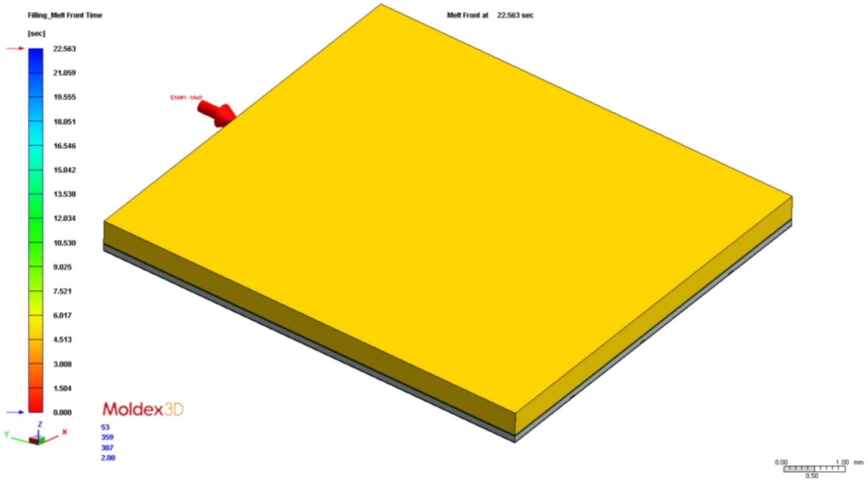
Injection molding to cooling

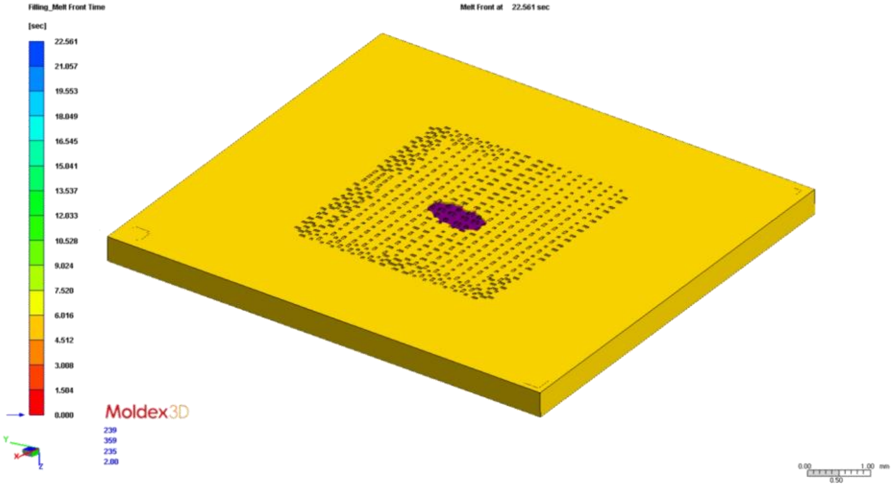
Post Mold Cure

Subsequent SMT reflow simulation

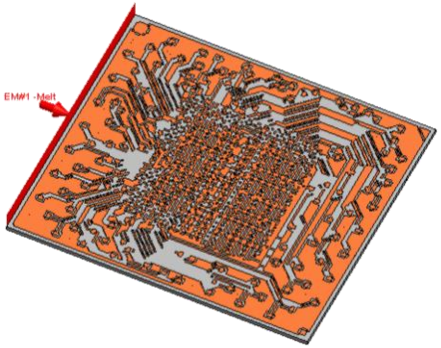
Mold Flow Simulation

The mold flow front encapsulates the cavity uniformly and has the potential to trap voids underneath the chip in C4 region.

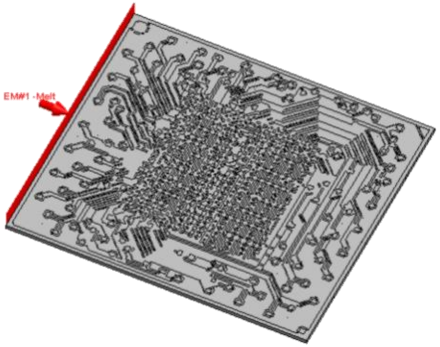




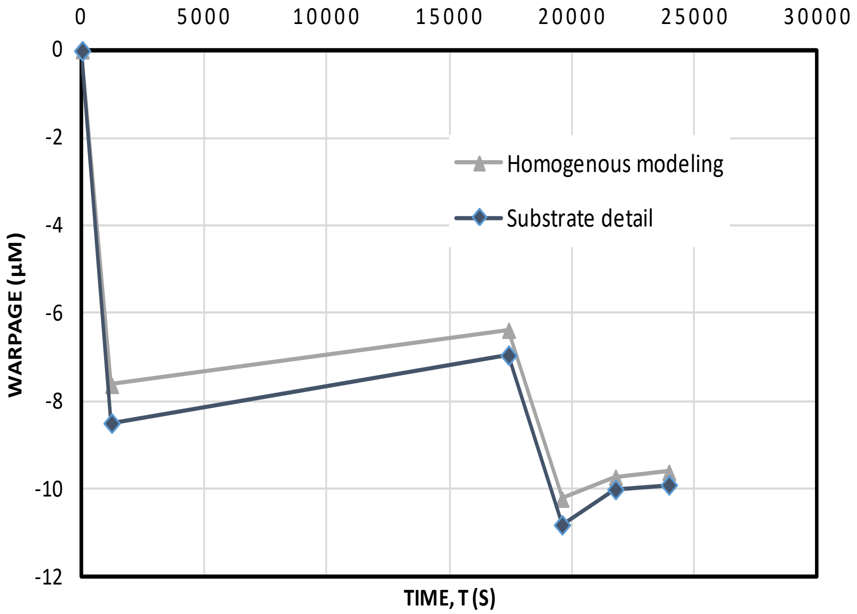
Effect of Detail vs Homogeneous Model



Detail Model



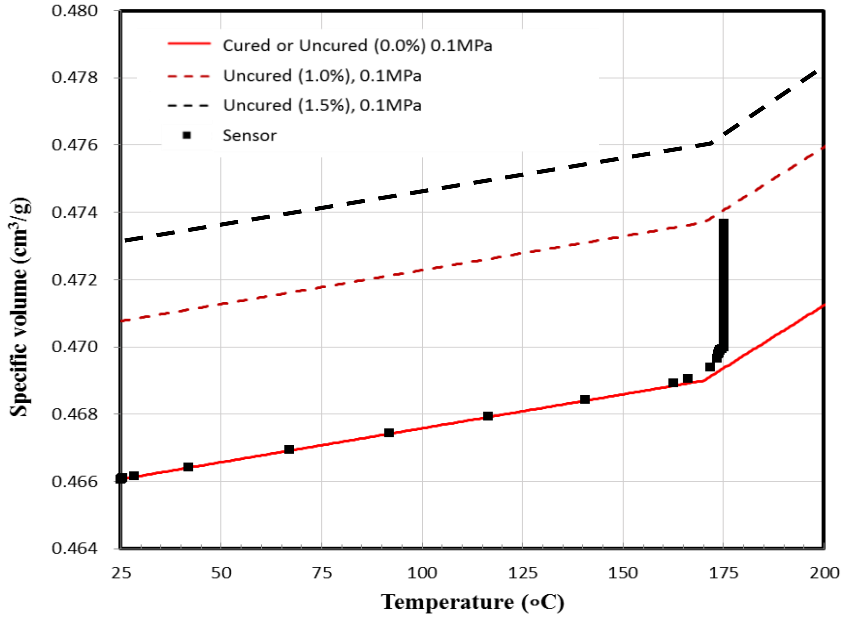
Homogeneous

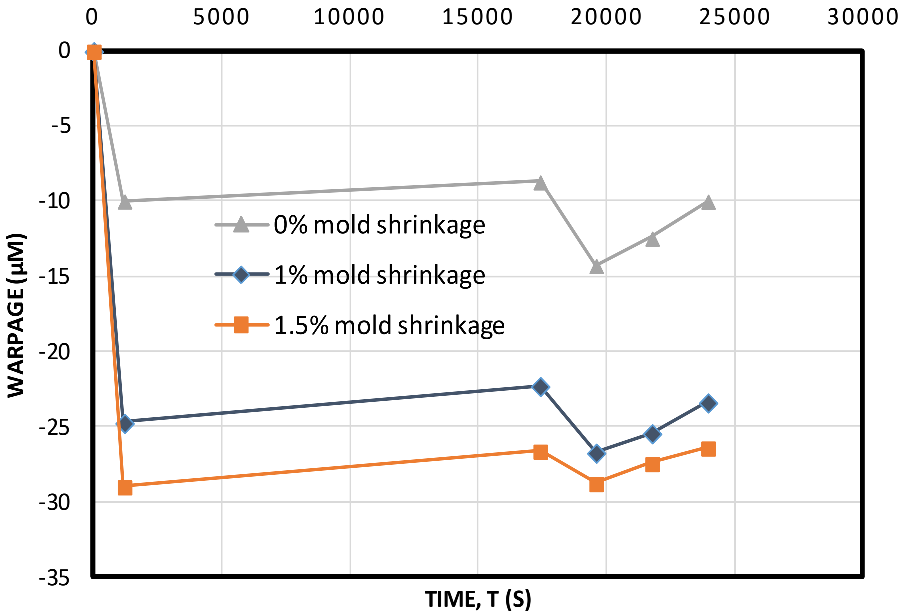


Detail Model – copper and dielectric patterns are taken into account
Homogeneous – the effective mechanical properties are considered

The impact of the detail model for this case is ~3% (not significant) due to small and thin design

Effect of PVTC Properties

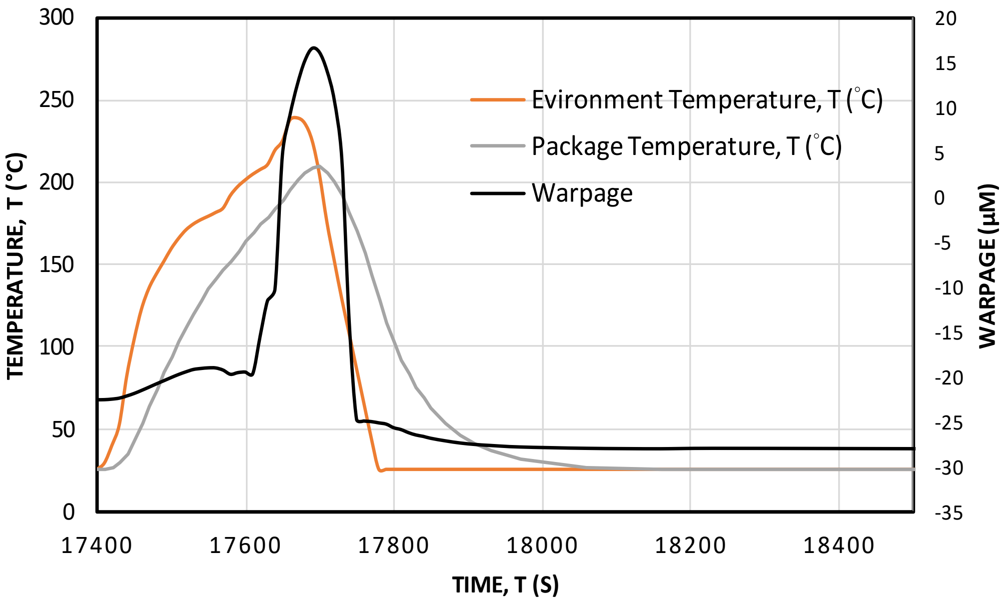


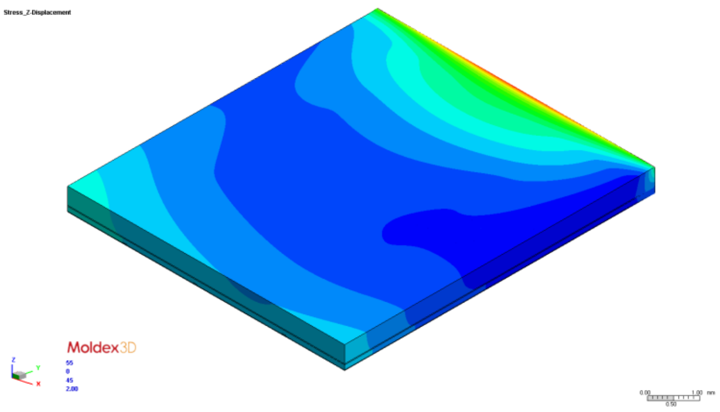


PVTC properties captures the volumetric change as a function of temperature for uncured and cured mold

The impact of mold shrinkage is significant. Typical FEA doesn't account for chemical shrinkage

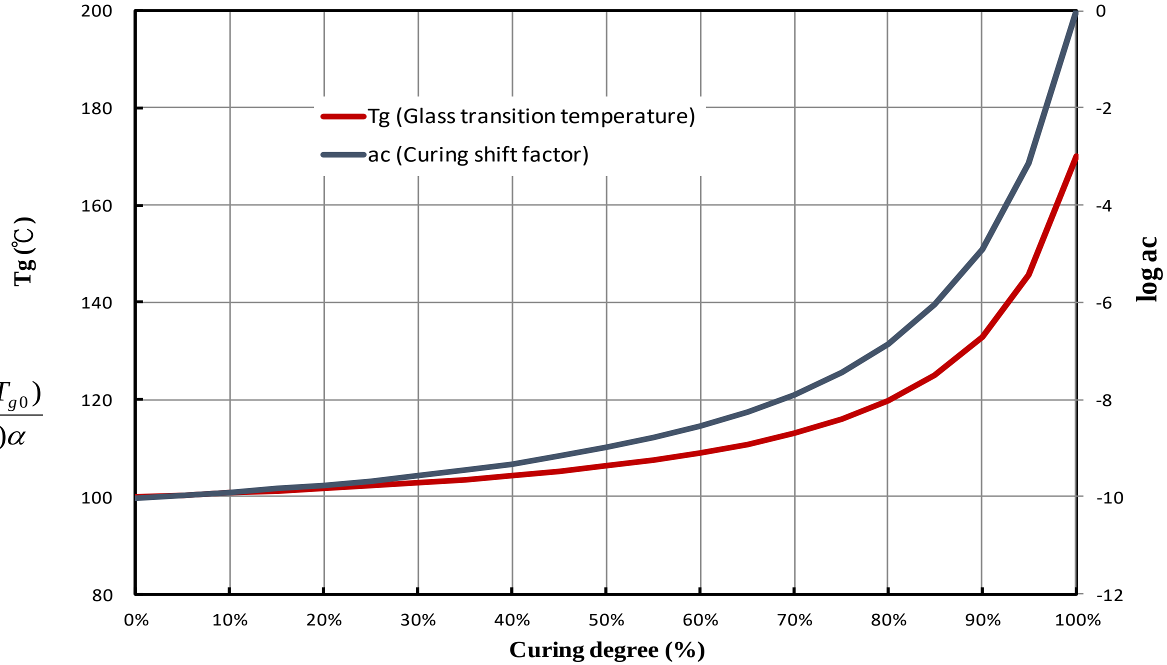
Dynamic Warpage of Package





During the reflow cycle, the package warpage changes as a function of temperature. The package started off concave (-ve) at room temperature, then morph to convex at elevated temperature

Effect of Tg as a function of curing degree



DiBenedetto

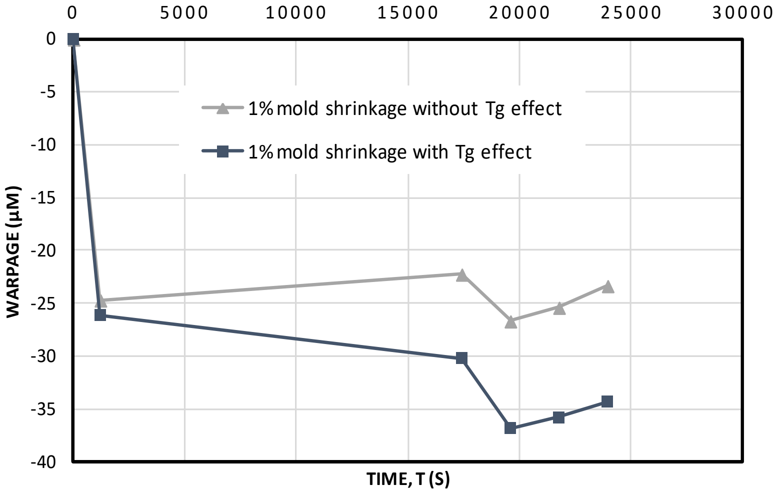
$$T_g(\alpha) = T_{g0} + \frac{\lambda\alpha(T_{g1} - T_{g0})}{1-(1-\lambda)\alpha}$$

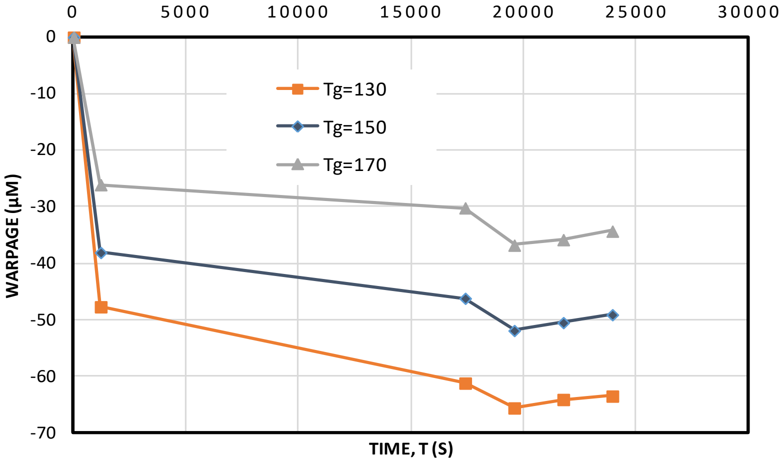
Vogel

$$a_c = \exp\left(-\frac{\Delta H}{R}\left(\frac{1}{T_g(\alpha)} - \frac{1}{T_{g1}}\right)\right)$$

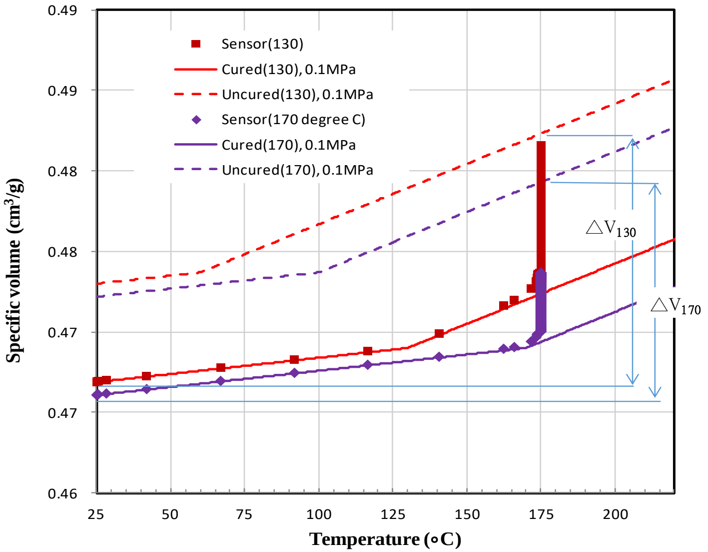
"DiBenedetto equation " is usually adopted for modeling the Tg as a function of conversion rate of reaction
the curing shift factor, ac, utilizes Vogel model

Effect of Tg





The evolution of Tg as a function of curing degree



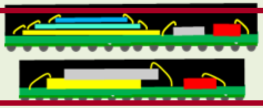
Lower Tg gives rise to higher warpage magnitude

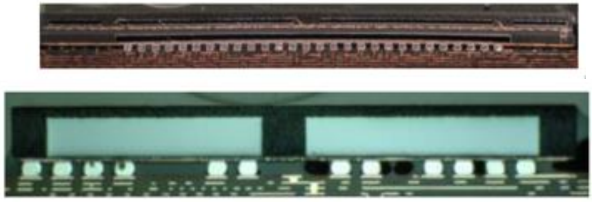
Summary

- Capturing the packaging assembly process involved requires significant effort in refining the assumptions, the numerical approach, and the analytical approach.
- The sensitivity model studied here only covered the molding process by capturing the mold flow and structural analysis based on fluid dynamics, PVTC, viscoelasticity with corresponding analytical equations and non-linear properties.
- The in-mold cure shrinkage which was represented by PVTC data, played a significant role in determining the final package warpage.
- A higher cure shrinkage can yield a higher package warpage.
- The impact of mold cure conversion rate on Tg and PVTC can change the characteristic of package warpage from uncured to fully cured mold.
- The modeling demonstrated that a higher cured Tg mold gives rise to a lower package warpage.
- The additional reflow cycles included in the model increases the package warpage as the result of changes in the viscoelasticity and stress relaxation.
- The next logical step is to evaluate other modeling approaches and validation that can mimic the actual assembly process as close as possible to enhance the prediction capability.

Package Technology Dynamic Warpage Measurement

Generous Donation of Samples from Industry

Package Type	*Design*	*Phase 2 and 3 Package Consideration*	*Phase 4 Package Consideration (New focus areas)*
PoP	Overmold TMV®		New PoP package (InFo-Integrated Fan out, WLP-wafer level packaging) Integrated memory and logic packages Latest MCeP (Molded Core Embedded Substrate) packages
	Expose Die TMV®		
	Bare Die PoP		
	Interposer PoP		
	Pre-stack PoP package		
	MCeP®		New variance - MCP
	PoP Memories		
SiP	Overmold Multiple Chip Package (MCP)		Modem and High Bandwidth Memory Packages
FBGA	Overmold single die package		
FCBGA	with single or multi dies		Multi-chip packages
FCBGA with Lid	Organic and ceramic substrate		Silicon Interposer Packages and embedded bridge
PBGA	Ranges		



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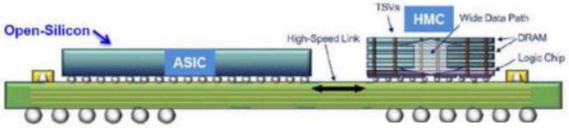
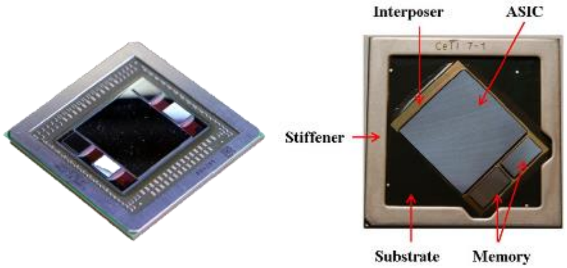
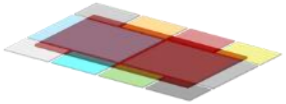




Industry Standard 2.5D



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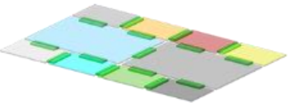

Focusing on new and advance package technologies

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