Microelectronics Reliability 62 (2016) 26–38

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Numerical investigation and experimental validation of residual stresses building up in microelectronics packaging

A.R. Rezaie Adli *, K.M.B. Jansen

TU Delft, The Netherlands

ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form 15 February 2016
Accepted 10 March 2016
Available online 16 April 2016

Keywords:
Epoxy molding compound
Viscoelasticity
Numerical
Modeling
Encapsulation
Packaging
Residual stress
Shrinkage
Thermosetting polymer
Conversion
Cure kinetics
PVT
DMA
DSC
Rheometry
Piezoresistivity

ABSTRACT

This paper comprises the numerical approach and the experimental validation technique developed to obtain the residual stresses building up during encapsulation process of integrated circuits. Residual stresses can be divided into cure and cooling induced parts. The curing originated stress had been mostly neglected in the literature and a special attention had always been given to detection of the thermal induced stress. In this study, both of the residual stresses, evolving during packaging, were investigated independently. The material behavior of the epoxy molding compound, EMC, was determined by the series of characterization experiments. The volumetric behavior of the EMC was investigated using PVT analysis, in which the total cure shrinkage of an initially uncured sample and the coefficient of thermal expansion of the same sample after full conversion were determined. The cure kinetics was studied using differential scanning calorimetry, DSC. The dynamic mechanical behavior was examined by dynamic mechanical analysis, DMA, at a fixed frequency. Besides, the time dependent behavior of the EMC was also determined by implementing the time–temperature superposition, TTS, test set-up in DMA. The shift factor was modeled using the combination of the WLF equation and the polynomial of second degree. The constitutive equations were developed based on the applied boundary conditions and the epoxy compound's mechanical behavior in the respective stage. A two dimensional numerical model was constructed using a commercially available finite element software package. For the experimental verification of the numerically obtained residual stresses a flexible board with the stress measuring chip was encapsulated. The real-time stress data were measured during the encapsulation. Using this technique, the in-plane stresses and the temperature changes during the die encapsulation were measured successfully. Furthermore, the measured stress data was compared with the predicted numerical results of the cure and the thermal stages, independently.

1. Introduction

Integrated circuits are used in various electronics and electromechanical devices. The range of applications is extensive, covering from the consumer electronics like smart phones and laptops to more advanced aerospace or military devices. Depending on the application type, the instruments are exposed to various environmental and processing conditions like moisture, mechanical stress, thermal stress or radiation, which all have negative impacts on the mechanical properties of the package. Any failure in electronic components may lead to failure of the whole device or part in which they are installed. Protection of electronic components from any external environmental effect or process-induced thermo-mechanical loading can be achieved by the encapsulation.

ICs are encapsulated by an epoxy molding compound. The EMC is a thermosetting polymer with unique properties providing thermal and mechanical protection, electrical resistance, shield against moisture and protection in handling the package by providing mechanical stability and support. The transfer molding is a standard process used for die packaging where the pellets of EMC are placed into the preheated chambers and are forced by a plunger into the enclosed mold cavity comprising a substrate and the integrated circuits. The EMC cures at the predefined mold temperature and after full conversion the encapsulated package is released. This process is not stress-free. The residual stresses are developed during molding in the internal components.

The residual stress prediction during and after the thermosetting epoxy cure has been studied in the past based on either elastic or viscoelastic mechanical models [1–10]. This paper is a combination of both models, depending on the conversion degree and the thermal state. The stresses in multilayer structures can be decomposed into mechanical, thermal and intrinsic parts. Thermal and intrinsic stresses are defined as the residual stresses. In epoxy molding, the intrinsic stress refers to the polymerization induced stress which is generated as a result of cure shrinkage of the epoxy. During the isothermal cure, the EMC shrinks while the other components do not experience any deformation. Contraction of the epoxy leads to a compressive force on the die beneath it. At the end of the cure, the mold clamp is released

---

* Corresponding author.

http://dx.doi.org/10.1016/j.microrel.2016.03.015

automatically and the board is removed from the mold cavity. As a result, the temperature of the entire package gradually drops down to room temperature. But the total thermal shrinkage levels of the package components are not the same. Hence, the thermal shrinkage mismatch between the cured epoxy and the other components, during cooling, results in residual stress build up in the package.

2. Mechanical modeling during cure and cooling

Mechanical constitutive modeling of the curing polymer involves complex interrelations of time, temperature and conversion variables. The stress generation during encapsulation process is attributed to the two phenomena; the strain due to shrinkage and the increase in modulus accompanying both isothermal polymerization and transient cooling.

2.1. Temperature dependent elastic modulus

Fig. 1 shows a typical elastic modulus of a fully cured EMC, which was obtained in DMA using the tensile test set-up at a high constant frequency and under infinitesimal strain. In this measurement a strip of fully cured EMC sample was heated with a constant rate starting from room temperature to 230 °C, covering the entire viscoelastic region. Using this method one can easily determine the maximum tensile modulus for the tested temperature range. As it can be observed clearly in Fig. 1 the modulus is in equilibrium rubbery state at higher temperatures. At the equilibrium state, the deformation time as well as the temperature variations does not have strong influence on the stress level. Since a typical encapsulation molding process is conducted at 175 °C ± 5 °C, it can be considered that the EMC modulus during isothermal cure stays within the limits of the equilibrium region. For that reason, in the cure stage the elastic constitutive model provides a satisfactory description of the mechanical behavior and therefore, the time dependent variations can be neglected as far as the temperature remains constant at the predefined mold temperature.

The change in degree of conversion leads to dramatic variations in physical properties of the epoxy during molding. Hence, although the time dependent behavior during isothermal cure is neglected, the rubbery modulus should be evaluated as a function of conversion.

2.2. Conversion dependent equilibrium modulus

An uncured sample of the EMC was cured isothermally at a constant frequency using the shear sandwich test setup in DMA. The isothermal temperature was set above the glass transition temperature to avoid vitrification. The effect of crosslink on the modulus of the epoxy can be seen in Fig. 2. The high glassy modulus instantly drops close to zero at the start of the measurement when the sample melts. The lower modulus is associated with the viscous fluid behavior of the epoxy melt before gelation. The modulus starts rising upon passing the gel point. Close to complete conversion, the modulus levels off. This is the time when the cure shrinkage is almost completed and the glass transition is close to its maximum value. Furthermore, the viscosity and the equilibrium stiffness of the sample are at the highest attainable levels for the tested cure temperature. The rubbery shear modulus is obtained as 240 MPa at the complete conversion.

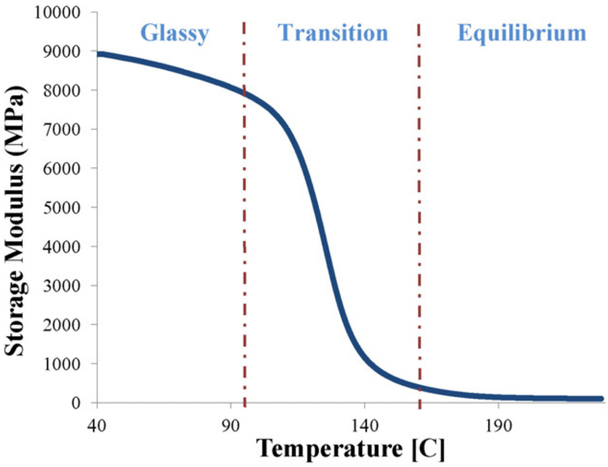

Fig. 1. Temperature dependent modulus which is determined using DMA by heating ramp of the fully cured EMC under high frequency and low strain.

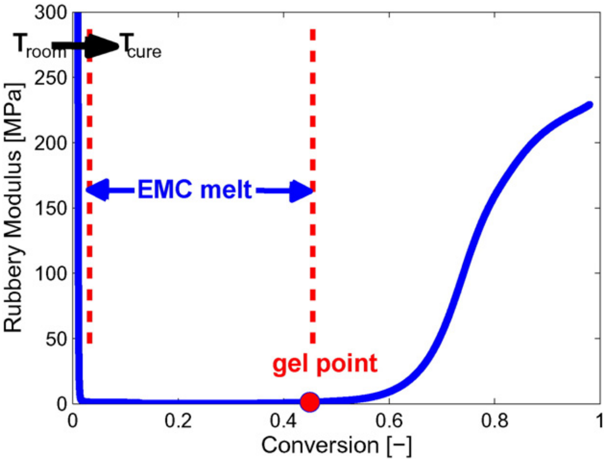

Fig. 2. Rubbery modulus as a function of conversion during isothermal curing of an initially uncured resin determined by DMA shear sandwich measurement.

Based on the experimental observations of Figs. 1 and 2 the mechanical behavior of the epoxy resin during cure stage is considered as elastic and conversion dependent. The conversion dependent equilibrium modulus was modeled using the Martin and Adolf scaling theory [11]

$$G_\infty = G_\infty^f \left(\frac{\xi^2 - \xi_{gel}^2}{1 - \xi_{gel}^2} \right)^{8/3}, \tag{1}$$

where $G_\infty{}^f$ is the rubbery shear modulus of the fully cured epoxy. ξ denotes the degree of conversion which is between 0 and 1, symbolizing the uncured and the fully cured states, respectively, and ξ_{gel} refers to the conversion level at the gel point.

2.3. Viscoelastic constitutive modeling in cooling

The total residual stress in packaging is the sum of stresses built-up after cure and cooling of the epoxy. As stated above, the mechanical behavior during cure is assumed purely elastic with the conversion dependent equilibrium modulus. However, this assumption cannot be applied to the cooling stage where the epoxy compound's mechanical response is time dependent. Therefore, the viscoelastic constitutive model should be introduced for the cooling stage. It is assumed that the stress is homogenous and isotropic. Then, the stress relaxation can be defined by [12]

$$\sigma_{ij}(t) = 2\int_{-\infty}^{t} G(t-t')\dot{\varepsilon}_{ij}dt' + \int_{-\infty}^{t} \left[K(t-t') - \frac{2}{3}G(t-t') \right] trace(\dot{\varepsilon}_{tot})\delta_{ij}dt', \tag{2}$$

Table 1
Cure kinetics model parameters.

A [1/s]	E_a [kJ/mol]	m [−]	n [−]
1.95×10^7	77.5	0.216	1.267