Advanced Virtual Qualification Methods to Reduce the Time-to-Market of Microelectronic Assemblies

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ABSTRACT

This work presents some recent progresses in reliability assessment of electronic assemblies in automotive industry and shows how coupled numerical-experimental techniques can help save time and reduce the cost of IC package qualification. In order to fulfill the continuous trends in miniaturization of the electronic devices together with the demand to shorten the time to market, it is essential to use virtual qualification methods with the simulation tools. One of the main concerns in electronic packages is the structural integrity during their fabrication, surface mount process, and service life. A prominent example of failure in electronic assemblies is the interface delamination between two dissimilar materials. This failure mode is accelerated when the polymeric materials absorb moisture from humid environments. Moisture results in degradation of the physical properties of polymers, induces additional deformation due to hygroscopic swelling, and more importantly, degrades the adhesion strength of the polymer to metal joints.

Keywords: Plastic IC package, delamination, moisture, finite element analysis, fracture mechanics

1 INTRODUCTION

Interface delamination between dissimilar materials is one of the major threats to the structural integrity and reliability of multi-layered structures. In many of these structures, such as microelectronic assemblies, one or more of the materials are made of polymers. In this case, moisture poses a significant threat to the reliability of these products and can be regarded as one of the principal causes of many premature failures [1,2].

Epoxy Molding Compounds (EMCs) are widely used as encapsulating materials in semiconductor packaging industry. The interface between EMC and the copper-based leadframe in plastic IC packages has been found to be one the weakest joints. Most cracks in plastic encapsulated microcircuits initiate and propagate along this interface. The crack propagation facilitates, when the EMC materials absorb moisture from the environment [3]. This paper provides a comprehensive overview of the primary mechanisms responsible for the interfacial delamination due to the presence of moisture and shows how coupled numerical-experimental techniques can help save time and reduce the cost of IC package qualification.

The methodology developed in this study to investigate the interface delamination between epoxy molding compound and the copper-based leadframe of a plastic IC package is as follows:

- Process-induced stresses during the fabrication of the plastic encapsulated devices are taken into account. The method was previously benchmarked by comparing the warpage of a simple biomaterial beam with the results from Finite Element (FE) analysis [2].
- Next, the moisture absorption of the plastic package is modeled by FE analysis. In separate studies [1-3] several test specimens were used to investigate the diffusion of moisture in epoxy molding compound and novel simulation techniques were proposed and validated.
- The hygroscopic swelling of the polymers upon moisture absorption is modeled. The value of the coefficient of hygroscopic swelling is determined experimentally and implemented in the FE code [3].
- The adhesion between the epoxy molding compound and leadframe is determined in terms of interfacial fracture toughness. Several test specimens, preconditioning and load set ups were used to determine the toughness as function of temperature, moisture and mode angle [4].
- Finally the fracture mechanic method is applied to analyze the interface reliability. The energy release rate is compared against interfacial fracture toughness and the delamination risk is evaluated.

This work provides conceptual understandings of the problem of moisture-driven interface delamination in plastic encapsulated microcircuits. In addition, it is shown how the developed method can enhance the material selection in order to improve the delamination resistance in the package and preserve the structural integrity.

2 MOISTURE DIFFUSION IN PLASTIC IC PACKAGES

Fig. 1 summarizes a number of effects associated with moisture diffusion in polymeric materials of electronic packages. Obviously, the prerequisite to investigate any moisture effect is to ascertain the diffusion (absorption and desorption) mechanism of moisture. Among the various effects listed in Fig. 1, three mechanisms are extremely important for the reliability of plastic IC packages from the structural mechanics point of view. First, the adhesion between the epoxy molding compound and other package materials (this work focuses on the copper-based leadframe) is of particular importance. This is because of the fact that under poor adhesion, the structural integrity of the package may be threatened, which may lead to disruption in sending electrical signals to the board. Second, the hygroscopic swelling is of particular concern since the resulting dimensional change alters the stress state in these parts. The third mechanism associated with moisture absorption is the effect of vapor pressure. This mechanism has normally significant influence at elevated temperatures of the solder reflow process. The main reason for the vapor pressure effect is the evaporation of condensed water molecules in the molding compound. This is especially important for the lead-free soldering because of the exponential increase of vapor pressure with elevated temperatures. Vapor pressure can be categorized into two types. One type is the micromechanics-based vapor pressure that causes the volume of the molding compound to increase, and hence, causes an additional mismatch between volumetric changes inside the package. The second type is the effect of gathered vapor molecules at delaminated interfaces. This acts as an additional driving force for the crack propagation and finally popcorn cracking of the package.

Presence of moisture in the package is the primary reason for the initiation of interface delamination during the solder reflow process. Moisture diffuses into the package during storage in ambient. The diffusion curve consists of two regions [1]. The first region shows a linear increase in concentration followed by an apparent saturation which can be modeled by a Fickian diffusion model. However prolonged exposure causes an additional linear increase in moisture concentration followed by a secondary saturation region. Therefore the total moisture uptake of the molding compound cannot be modeled using Fick's Law and a more complex model was developed [1] which is applied in this study.

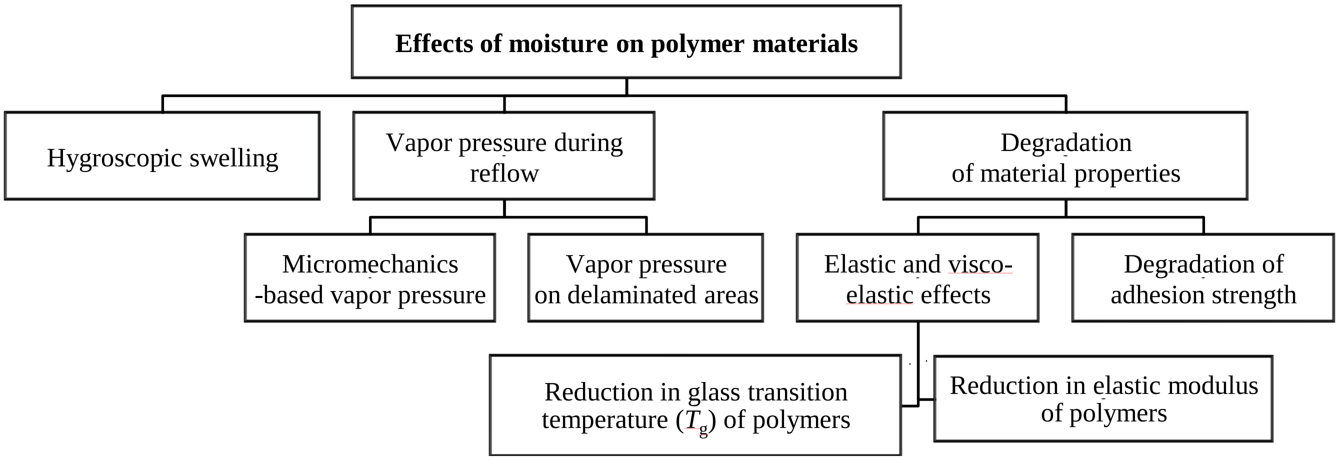
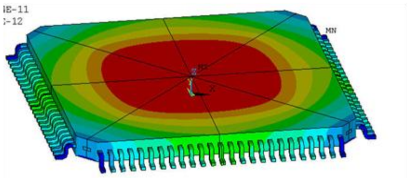


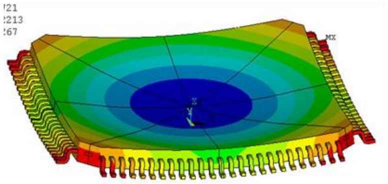
Figure 1: Effect of moisture on the polymeric materials of plastic IC packages.

3 THERMO-MECHANICAL ANALYSIS

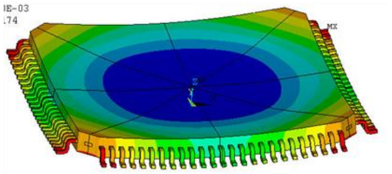
Finite element (FE) analyses were carried out on a TQFP-epad package that uses a commercial epoxy molding compound. This material is completely characterized for a complete thermo-hygro-mechanical FE analysis [1-4]. Fig. 2 shows FE results of this package. Fig. 2a shows the state of the deformations in package during the transfer molding while the epoxy molding compound is still in fluid state. When cross-linking in the EMC material commences, it shrinks and causes deformation of the package at molding temperature as shown in Fig. 2b. When cooling to room temperature, the mismatch between the CTE values of different package materials causes thermal strains to develop. This is the second mechanism causing deformation in the package as shown in Fig. 2c. A third mechanism shown in Fig. 2d is the moisture-induced hygroscopic swelling. Since the chip and leadframe of these packages are impermeable to moisture, the absorption of moisture by EMC materials causes a further deformation in package as shown in Fig. 2d, changing the deformation state from a “smiling” to a “crying” form.



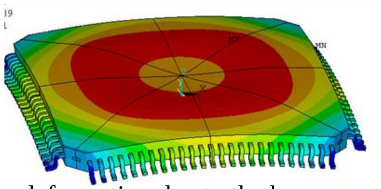
(a) Injection of EMC and transfer molding at 175°C.



(b) Curing at 175°C and deformation due to shrinkage of EMC during the polymerization.



(c) Cooling to room temperature and deforming due to CTE mismatch between package materials.



(d) Further deformation due to the hygroscopic swelling of EMC during moisture absorption.

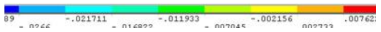


Figure 2: Deformation of a TQFP-epad package after (a) mold injection (b) manufacturing (c) cooling (d) moisture preconditioning.

These examples indicate that any temperature change or moisture absorption can act as a driving force for interface delamination. In the following section the same package will be investigated under temperature cycling test. This example attempts to show how fracture mechanics can be used to predict interface delamination between the copper-based leadframe and epoxy molding compound. By adding a precrack to an interface in the model it is possible to find the strain energy release rate.

4 FRACTURE MECHANICS ANALYSIS

In order to estimate the delamination risk based on a fracture mechanics approach, two essential parameters must be estimated and compared to each other. The first parameter is the Strain Energy Release Rate (SERR or shortly G) which is the driving force for crack propagation. The second parameter is the critical value of G, known as interfacial fracture toughness (G_c) which represents adhesion strength. Ref. [4] presents some experimental testing methods performed in this work in order to determine the interfacial fracture toughness between epoxy molding compound and the copper-based leadframe.

Once the interfacial fracture toughness is known, it is possible to predict as to whether the loading condition is able to cause an existing crack to propagate. Fig. 3 illustrates the methodology to predict interfacial delamination in plastic IC packages.

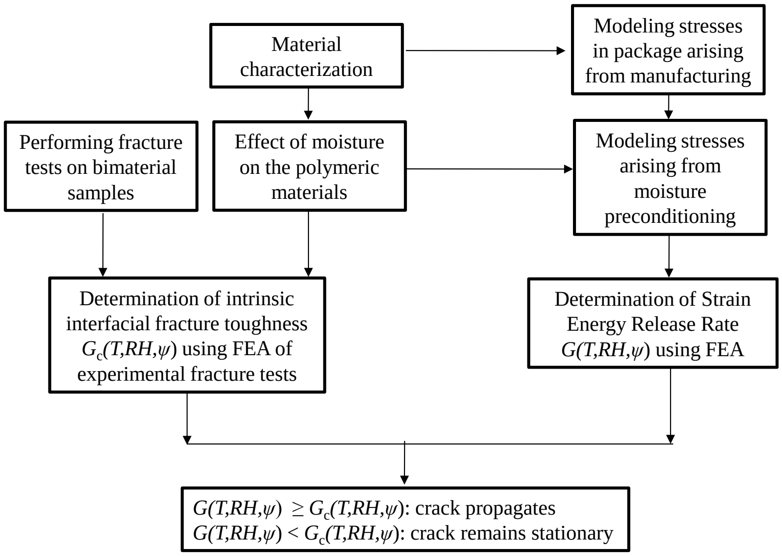
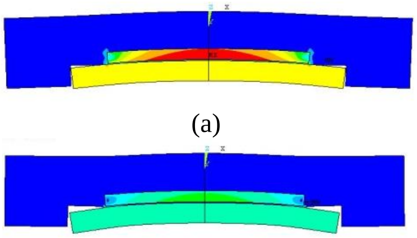


Figure 3: Methodology to predict the interface delamination by a combined fracture mechanics and thermo-mechanical analysis.

Fig. 4a shows an FE-simulation of this package with a very short pre-crack length at leadframe/epoxy molding compound interface. The FE model was done using a parametric script for the finite element tool ANSYS. The crack length was varied and the analysis was carried out at each step. Fig. 4b shows the same package while the pre-crack length was assumed to be quite larger. The nodal loads and displacements were exported for the further post-processing to determine the components of the strain energy release rate. A temperature change of 150°C to -40°C was used as the loading, which mimics the first half of a temperature cycle.


(a)

(b)

Figure 4: FE modeling the crack at leadframe/EMC interface of a TQFP-epad package. (a) short crack, (b) long crack.

The energy release rate and the mode angle of crack at the leaframe/EMC interface based on the asymptotic linear elastic stress field are determined by Virtual Crack Closure Technique (VCCT). Fig 5 shows the strain energy release rate as a function of the crack length. From this figure it is evident that the energy release rate in this package depends on the crack length at the interface. For short crack lengths the strain energy release rate remains almost constant at moderate values. The *G* value is smaller than the interfacial fracture toughness found in [3,4] for the respective mode mixity. This means that an existing crack with the length below 0.5 mm does not pose a potential risk regarding the crack propagation during a temperature cycle. This is in agreement with the experimental temperature cycles performed on these packages, where it was observed that the length of delamination after the solder reflow process determines if the crack would propagate during subsequent temperature cycles. Moreover, as shown in this figure, the mode mixity at the crack tip varies between 4 degrees for very short cracks up to approximately 15 degrees for large cracks of around 1 mm length. This means that the fracture mode in this package is mainly dominated by mode I fracture. Since the interfacial fracture toughness of this interface is known through the experimental part [3,4], it is possible to determine the critical pre-crack length, which leads energy release rate to exceed the interfacial fracture toughness and hence enable crack propagation. Obviously, this critical length of the pre-crack is different for packages that have experiences various humid environments. This is because of the fact that by exposure to moisture the adhesion strength of interfaces decrease as observed in [4].

When moisture is available, the first step is to determine the state of moisture concentration. In the most simple form, by assuming one week sorption at 85°C/85%RH the interfacial adhesion is almost 40% lower than that for dry package [4]. Due to the relatively short diffusion path to interface because of thin geometry of package, the moisture concentration may most probably reach the second phase of the absorption curve as described in [1-3]. This means that there would be no recovery in adhesion when the samples are baked prior to temperature cycle. As a result of adhesion degradation, in the case of one week prior sorption at 85°C/85%RH, the critical crack length of moisture-preconditioned package is almost 0.2 mm. This indicates that crack propagation at the interface of moisture treated samples is possible with smaller initial crack length as compared to dry samples.

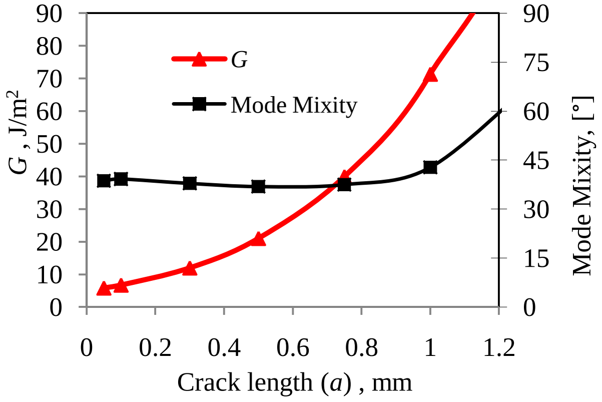


Figure 5: Strain energy release rate and mode mixity of interfacial crack are plotted as a function of crack length.

5 CONCLUSIONS

In order to reduce the time-to-market of microelectronic assemblies it is important to use finite element analysis to predict possible failure modes. The structural integrity of plastic IC packages can be more likely preserved, if they are designed according the virtual qualification results. In order to prevent interface delamination between the EMC and other materials, fracture mechanics can be used to assess the delamination risk. In this case the crack driving force, *G*, should be compared with the fracture toughness G_c and the crack propagation happens if G exceeds G_c. Effects of moisture diffusion, package design and material combinations were investigated and good correlation between the predicted and experimental results was observed.

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