Effect of Postmold Curing on Plastic IC Package Reliability

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ABSTRACT: Nearly all IC encapsulating compounds require a postcure treatment to ensure integrated circuit (IC) package reliability. The issue of postcuring and this effect on IC package reliability performance are considered in this article. We examined the development of various encapsulating compounds' properties with various durations of postcure time. It was found that the mechanical strength, glass transition, and adhesion strength were increased with increasing duration of postcure time compared to as-molded samples. However, these properties could reach ultimate values after postcuring for 1–2 h. It was also seen that the moisture uptake was increased for samples that have been post-mold-cured due to increased crosslinking density causing a large free volume in the glassy polymer matrix. C-mode scanning acoustic microscopy (C-SAM) analyses were performed to investigate the effect of the duration of postcure time on the IC package reliability and they show a good relationship with the evolution of the compound's properties during the postcure process. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 69: 2187–2193, 1998

Key words: epoxy resin; encapulating compound; plastic IC package reliability; post-mold cure; IR reflow solder

INTRODUCTION

In integrated circuit (IC) packaging, thermosetting polymers are important due to cost consideration in both manufacturing and material selection. Plastic packaging has, therefore, become the dominant method for protecting ICs from the environment. Today, more than 80% of all semiconductors are encapsulated with low-pressure molding compounds especially made from phenolic–novolac-cured epoxy resin.[1,2] *O*-Cresolnovolac epoxy resins have an advantageous pot life, formability, and humidity and heat resistance.[3] As chip size has increased rapidly and package dimensions have become smaller and thinner, the reliability of plastic-packaged IC devices has become a major concern. In particular, surface-mount plastic-molded IC packages often crack during the solder–reflow process required to mount them to a PCB board. The properties of molding compounds are an important parameter to evaluate the susceptibility of an IC package to delamination and crack.

Postmold curing is an integral part of plastic packaging because molding compounds do not reach 100% chemical conversion in the high production rate molding process. The reaction rate becomes slow significantly at the later stages of conversion, making elimination of postcure unlikely. The usual procedure used in the IC industry is to continue the reaction in the mold until the hot hardness reaches either a plateau value or a value that is suitable for ejection and to postmold cure at 170–180°C for 5 h. The various properties of molding compounds will reach their ultimate values during postcuring. Thus, postmold cure should affect on the IC package reliability. To date, most of the studies related to IC molding

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Table I Formulation of Epoxy Molding Compound

Raw Material	Parts by Weight
Epoxy resin (EOCN1020 or YX-4000)	88
Brominated epoxy resin (BREN-S)	12
Hardener (PN)	55–60
Accelerator (DBU)	1.0–2.5
Filler (fused silica)	700–1200
Flame retardant (Sb_2O_3)	10
Coupling agent (silane compound)	5
Release agent (Carnauba Wax)	2.5
Colorant (carbon black)	2

compounds have centered on the relationship between the fully cured compound's properties and IC reliability. Few studies have been performed on the subject of postmold curing effects on the various properties of the compounds. In this article, we are particularly concerned with the relationship between the physicochemical properties of molding compounds and IC package reliability with the change of postcure time.

EXPERIMENTAL

Materials

The epoxy resins used were *o*-cresol formaldehyde novolac epoxy, brominated epoxy (EOCN 1020 series and BREN-S, Nippon Kayaku), and biphenyl epoxy (YX-4000, Yukka Shell). Phenol novolac resin (HF series, Meiwa Kasei) and 1,8-diazobicyclo (5,4,0)-7-undecene (DBU) were used as a hardener and an accelerator for the curing of the epoxy resins, respectively. These resins were selected to formulate "epoxy encapsulating compounds" by mixing them with other additives as shown in Table I. Table II lists the chemical structures of the base resins and accelerator used for the experiments. To prepare the IC encapsulating compound, these materials were premixed in a Henschel mixer for 2 min at room temperature, and the blend was melt-kneaded at 110°C. Then, the mixture was cooled and crushed into a powder with a pin-type crusher, and, if desired, tableting. Each 40 g of powder was pressed in a mold cylinder with a 40-mm diameter under 50 kg/cm^2 to form a tablet. Silica fillers were surface-treated by spraying an aqueous silane with dry air or nitrogen gas under forcible agitation in a V-blender.

Thermal Mechanical Analysis

The glass transition temperature (T_g) of the epoxy molding compounds was measured with a TMA/SS-100 Seiko thermal mechanical analyzer. The test specimens ($5 \times 5 \times 15$ mm) were heated from room temperature to about 250°C at heating rate of 2°C/min.

DSC Measurement

The calorimetric measurement was conducted using a TMA/SS-100 Seiko differential scanning calorimeter with a microprocess controller. The temperature and power calibration of the DSC were optimized for the temperature of 20–300°C using high-purity indium. For the isothermal cure, the DSC was first equilibrated at the present cure temperature and then the sample was introduced into the DSC cell.

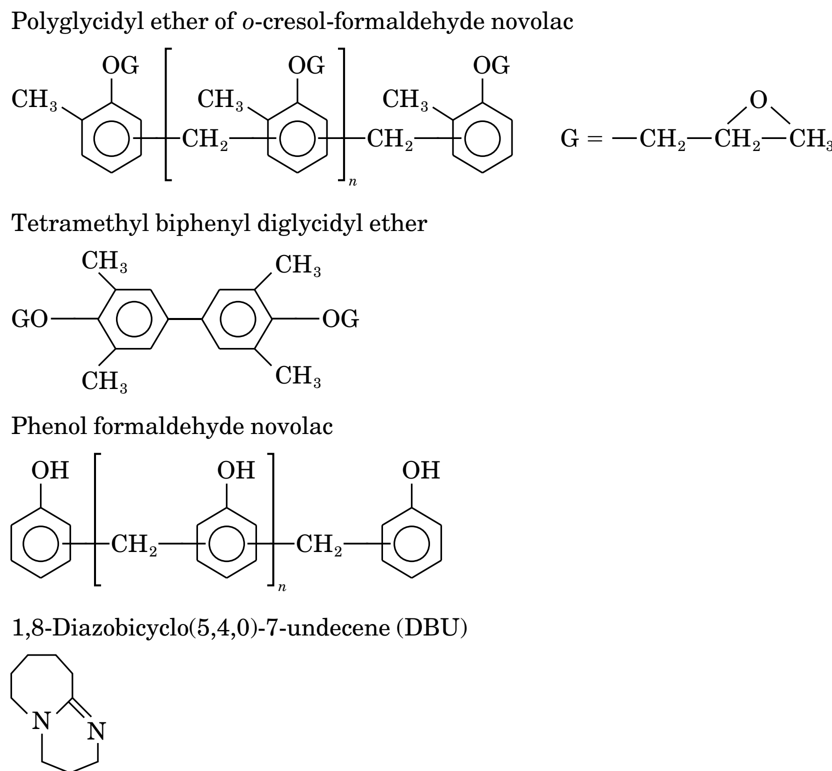
Mechanical Test

Mechanical characterization of the epoxy molding compounds was carried out using a Zwick universal testing machine with a high-temperature chamber operated from room temperature to 350°C. The flexural strength and modulus were measured by a three-point bending test with span interval of 64 mm and bending speed of 1 mm/min according to ASTM-D-790. The test specimens ($5 \times 12.7 \times 60$ mm) were prepared by transfer molding at 175°C for 120 s and cured in an oven at 175°C.

90° Peel Test

Peel test specimens of epoxy molding compounds of dimensions of 127 (L) $\times$ 12.5 (W) $\times$ 1.25 (T) mm were molded onto a thin aluminum foil (Tokai Foil Inc., Tokyo, Japan) by the conventional transfer-molding process. The adhesion test was performed on a Universal adhesion test machine operated at 0.5 mm/s. The adhesion strength was measured by the maximum force required to peel off the thin foil at a 90° angle from the rigid molding compound as shown schematically in Figure 1. The aluminum foil used for this study was chemically cleaned by acetone and hexane with ultrasonification and then dried with air. This was intended to eliminate any test variation due to contamination such as residual oils since it plays a key part in attaining consistent and reproducible test results.

Table II Chemical Structure of Base Resins and Catalyst



Scanning Acoustic Microscopy

A C-mode scanning acoustic microscope (C-SAM) was used for monitoring interfacial delamination and package cracking by exposure to an IR solder reflow. The C-SAM scan was performed using a SONIX system L/HF 200 equipped with a 15-MHz, 0.5-in. focal length transducer after preconditioning steps. This test utilizes a pulse–echo technique in which a high-frequency acoustic beam is focused on the interface within an IC package. The reflected acoustic wave coming from the interface is analyzed to determine if delamination or other defects are present. The preconditioning steps used for this study included (1) as-molded and (2) postmold curing from 0 to 5 h at 175°C, (3) 10 thermal cycles at −65 to 150°C (one cycle was 30 min at each low/high temperature), (4) moisture uptake at 85°C/85RH for 168 h, and (5) three times IR reflow solder.

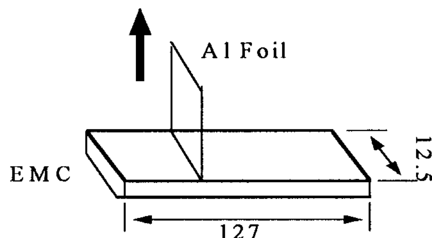


Figure 1 Schematic illustration of A1 peel adhesion test.

RESULTS AND DISCUSSION

The fundamental characteristics of the molding compound to consider in view of IC package reliability are the glass transition temperature, mechanical strength, moisture uptake, and adhesion strength. Here, we examined the behavior of these properties as a function of postcure time. The gel time of the compounds used in this study was controlled in the range of 24–26 s, since this is extensively applied for typical multiplunger machines with about a 70-s molding cycle.

First, the mechanical properties of the molding compounds were measured since they are critical to judge the molding compound's crack resistance. The three-point bending test is the most basic and most important material characterization test. It

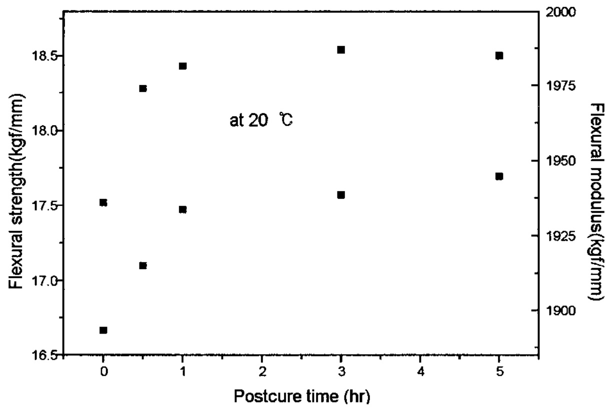


Figure 2 Effect of postcure on the mechanical properties measured at 20°C.

gives the flexural modulus and strength. Figure 2 shows the mechanical properties measured at room temperature before and after postcure. As can be seen, both the strength and modulus increase with increasing postcure time at room temperature. The mechanical strength and modulus increase up to 5.6 and 2.7% after postcuring for 5 h, respectively. Figure 3 also shows enhanced mechanical properties at 240°C: 19.4% for strength and 20.6% for modulus. It is interesting to see that the postcure effect on the mechanical properties at high temperature appears more clearly compared to the results at room temperature. Since the specimens were kept in a high-temperature chamber for 3 min before the measurement, the enhancement should be greater than the above values. The reduction of ultimate strength of the molding compound by nonpostcure could be very undesirable for package reliability. On the other hand, the mechanical properties

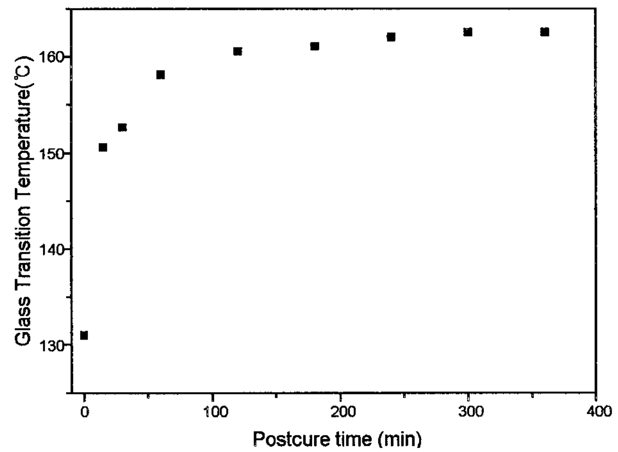


Figure 4 Effect of postcure time on glass transition temperature.

reach an ultimate value within 1 h, indicating that excess postcure is unnecessary.

Figure 4 shows the relationship between T_g and postcure time. The glass transition temperature was obtained from the inflection point of the coefficient of linear thermal expansion. It is seen that the T_g can increase up to 30°C after postcuring for 5 h. The T_g of the thermosetting resin is much influenced by the crosslinking density ρ, or molecular weight between the crosslinking points, indicating that the compound as-molded contains a considerable amount of nonreacted molecules and that the crosslinking density increases with postcure time, resulting in an increase in T_g. As the above results show, the T_g of the compound approaches the fully postcured state within 2 h.

To assess the extent of polymerization, an isothermal DSC thermogram of the molding compound was measured. Figure 5 shows that the

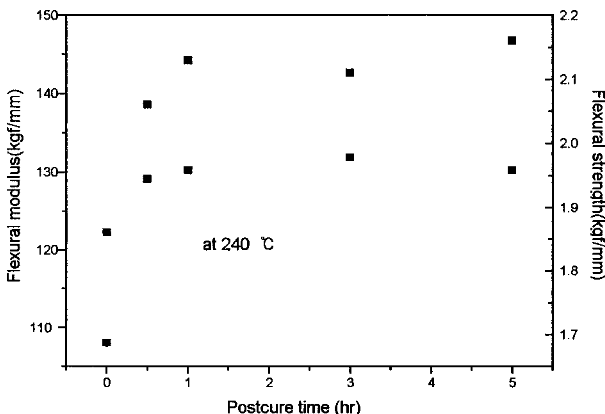


Figure 3 Effect of postcure on the mechanical properties measured at 240°C.

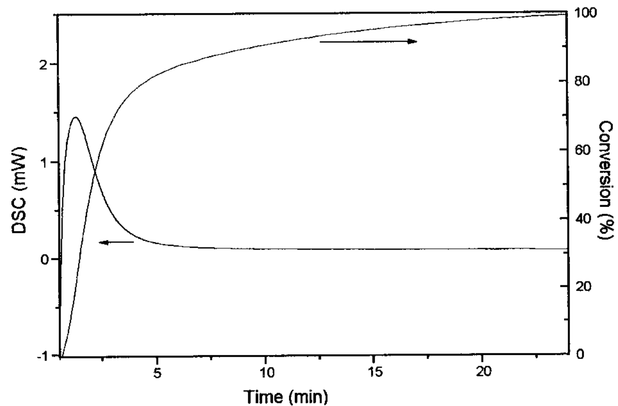


Figure 5 Plots of DSC and conversion versus time for an epoxy molding compound at 175°C.

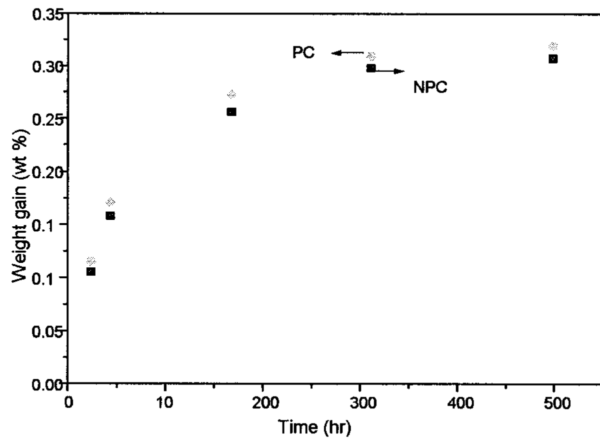


Figure 6 Moisture uptake measured at a 85°C/85 RH condition for a nonpostcure sample and a 5-h postcured sample.

cure rate of the epoxy-molding compound passes through a maximum point and then decreases. It also provides a plot of the conversion as a function of time. These results clearly show the initial rapid rate of the reaction and the drop-off in the reaction rate as the reactant is consumed due to the diffusion-controlled reaction mechanism. The DSC data show that a noticeable heat of reaction is not observed after 30 min, while less than 70% of the reaction progresses within 3 min.

The moisture uptake of the molding compound was monitored by percent weight gain measurements at a JEDEC Level I standard condition (85°C/85 RH) with a disk specimen (5-cm diameter/1 mm thick). The average of six samples was used in the weight-gain determination. Moisture absorption data are given in Figure 6 before and after postmold curing for 5 h. The moisture absorption increases rapidly at the initial stage and becomes concave toward the abscissa with time. Postmold-cured samples exhibit a greater moisture uptake and a larger diffusion coefficient compared to nonpostcured samples. It is very interesting since increased moisture uptake can cause additional stress in an IC package during solder reflow. Since moisture cannot penetrate the silica filler, the behavior of the diffusing moisture in composites should be affected by the cured resin properties. In general, the mobility of water molecules in a cured resin largely depends on the free volume and the free-volume size.[4–6] The change of the crosslinking density by postcure may cause a big difference in the free volume and packing state of cured resin molecules. For a highly crosslinked 3-dimensional network polymer like a phenol–formaldehyde novolac-cured *o*-cresol novolac-type epoxy resin, the crosslinking point acts to block close packing of the molecular chains, freeze micro-Brownian motion, and constrain the shrinkage of polymer matrix during cooling to room temperature. Thus, the specific volume would tend to increase as postcure time increases.

The A1 peel strength of the compounds with two different types of epoxy resins, *o*-cresol novolac type and biphenyl type, before and after postmold cure for 5 h is shown in Figure 7. These epoxy resins were selected since they are extensively used for IC encapsulation. The molding compound with biphenyl-type epoxy exhibits greater adhesion strength than does the molding compound with novolac-type epoxy. A biphenyl resin which has a lower molecular weight than that of the novolac-type epoxy resin renders a lower molten viscosity, which then favors the resin wettability to the substrate. It is known that the viscosity of the biphenyl-type epoxy resin is one-tenth of that of the *o*-cresol novolac-type epoxy. Similar results have been reported by others.[7,8] Figure 7 also shows that the molding compounds with both biphenyl and *o*-cresol novolac epoxy postcured for 5 h have better A1 peel strength than that of nonpost cured compounds. In this case, however, the improved adhesion does not come from the favorable wettability but from increased toughness by postcure, resulting in increased debonding energy or requiring more energy to detach the A1 metal sheet from the compound.

Delamination and package cracking during reflow soldering on a printed circuit board are the most critical issues for the reliability of plastic-

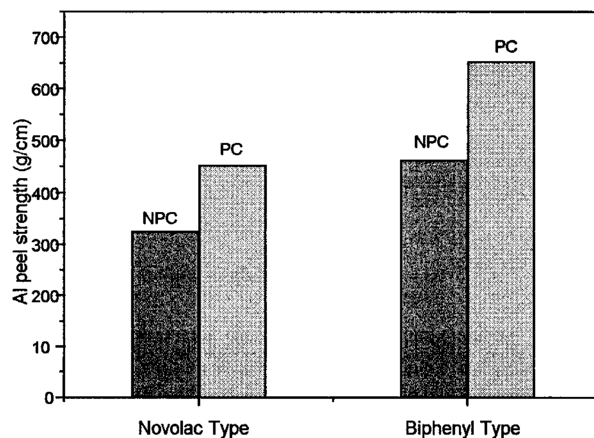


Figure 7 Effect of postcure on the adhesion strength of the epoxy molding compound.

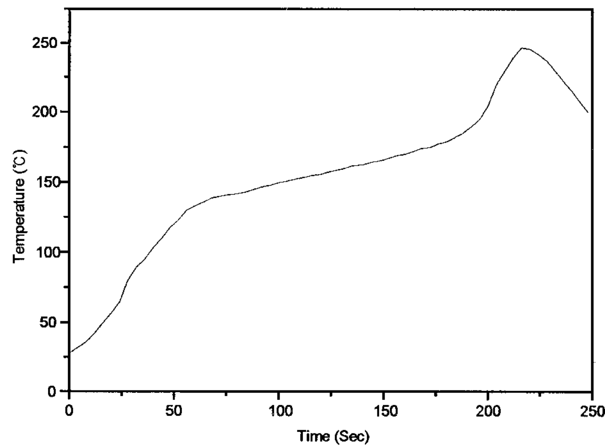


Figure 8 Temperature profile for the IR reflow test.

encapsulated semiconductor devices.[9–11] Fukuzawa et al.[12] reported the failure mechanism during reflow soldering. Plastic-encapsulated devices are permeable to moisture due to the hygroscopic nature of the typical epoxy molding compounds. The intense heat (to 260°C for some board assembly requirements) turns moisture into high-pressure vapor and builds up pressure inside the package, causing undue stresses at the various material interfaces. Once a critical stress threshold is reached, interfacial delamination occurs, followed by the package cracking of molding compounds known as "popcorn cracking." For package reliability studies, samples with various durations of postcure time were subjected to thermal cycling and moisture conditioning (85%/85 RH for 168 h, JEDEC Level I) followed by three times IR reflow to simulate surface-mount conditions. The temperature profile used is shown in Figure 8. Internal delamination and package crack were investigated using C-SAM followed by microsectioning. A typical C-SAM result and cross-sectional examination obtained for 20 SOJ devices are shown in Figures 9 and 10, respectively. Severe delamination at the die surface and package crack propagated sideway were detected for the nonpostcured sample. The delamination level was approximately 65%. It is also seen that the detected level of delamination on the topside of the die decreased as the duration of the postcure time increased. No die surface delamination and package crack were detected after postcuring for 1 h. This result clearly shows that postcure for several hours is unnecessary and has a similar trend with the data of the material properties measured at various postcure times. It is thought that the improvement in the IC package reliability during IR reflow solder after the postmold cure process results mainly from the enhanced adhesion and mechanical strength.

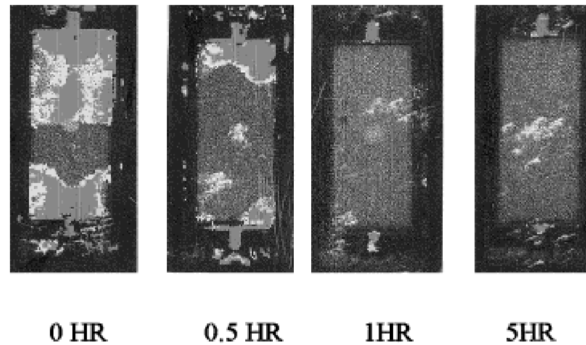


Figure 9 C-SAM image showing the effect of postcure on the interfacial delamination between the molding compound and the die.

In conclusion, postmold cure plays an important role in governing the material properties of IC molding compounds. It has been shown that full material properties including mechanical properties, moisture sensitivity, and adhesion strength could not reach ultimate values for as-molded samples prepared by transfer molding with a short cure cycle, but they could be reached within 1–2 h postcure. It has been demonstrated that C-SAM results have a good relationship with the cured state of molding compounds. This article has shown the feasibility of predicting moisture-induced defects such as delamination and popcorn crack during IR solder reflow by examining the evolution of the molding compound's properties during postcuring. This work ultimately leads to the optimum postcure condition in view of IC reliability and productivity.

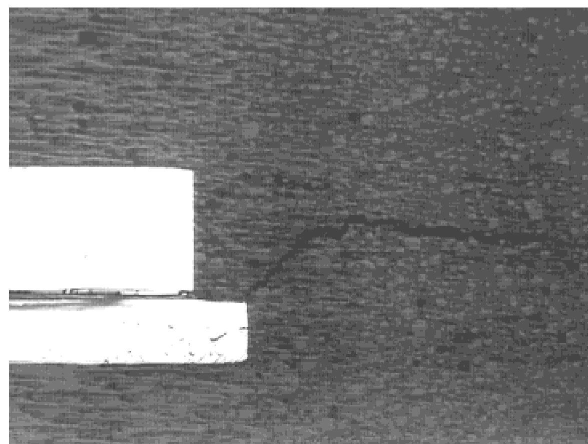


Figure 10 Cross-sectional view of a package where cracks propagate sideway.

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