Effects of Molding Pressure on the Warpage and the Viscoelasticities of HVQFN Packages

D. Y. Gui,[1,2] L. J. Ernst,[1] K. M. B. Jansen,[1] D. G. Yang,[1] L. Goumans,[3] H. J. L. Bressers,[3] J. H. J. Janssen[3]

[1]*Department of Precision and Microsystems Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands*
[2]*School of Chemistry and Chemical Engineering, Shenzhen University, Shenzhen 518060, People's Republic of China*
[3]*Philips Semiconductors, 6534 AE Nijmegen, The Netherlands*

Received 27 December 2005; accepted 5 December 2007
DOI 10.1002/app.28317
Published online 6 May 2008 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Molding temperature, molding pressure, and time are three major parameters affecting the curing quality of molding materials. In this article, the effect of molding pressure on warpage of HVQFN packages is studied. The typical map-chips with 65% silica particle-filled epoxy resin are manufactured under five molding pressure levels from 1.8 to 12.3 MPa. The curvature measurements are performed for the packages after demolding and postcuring, respectively. The viscoelastic tensile relaxation modulus of molding materials is obtained by using dynamic mechanical analysis. The characterization of evolution of equilibrium moduli is analyzed for future modification of the model. The experimental results show that the molding pressure has a significant effect on the warpage after molding as well as after postcuring of HVQFN packages. The curvatures of HVQFN packages at both lower (1.8 MPa) and higher molding pressures (12.27 MPa) are about 45% less than the average max curvature at 3.6–8.66 MPa. The molding pressure has obvious influences on the glassy Young's modulus but has little effects on the rubbery modulus and relaxation time of the package materials. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 2016–2022, 2008

Key words: molding pressure; warpage; viscoelasticity; electronic package

INTRODUCTION

Warpage causes a molded object to bend or twist out of shape and alters not only the dimensions but also the contours and angles of the object. Product warpage in molded polymer parts can have a major effect on product performance and is therefore undesirable. Warpage due to processing induced residual stresses has long been recognized as an important issue for package reliability. In electronic packaging, molding compounds are frequently used for encapsulation. During manufacturing processes, the combined chemical shrinkage and thermal expansion often result into undesirable product warpage. Excessive warpage not only causes device failure issues such as die cracking and interface delamination, but also may cause assembly problems in the subsequent processes such as due to dimension instability, noncoplanarity, etc.

Molding temperature, molding pressure, and hold time are three major parameters affecting the curing quality of molding materials. Therefore, investigation of the effects of process conditions on the warpage of IC packages is important for minimizing the warpage and residual stresses and the optimal design of the products.

In recent years, many efforts have been made to measure and/or predict process-induced warpage of packages. Most studies were focused on the effects of temperature and cure conversion on warpage of products and their viscoelasticity.

Kelly[1] measured the warpage of a plastic power package and indicated that the package was significantly deformed at the molding temperature, which is attributed to chemical shrinkage of the molding compound. In Ref. 2, the impact of processing conditions on warpage prediction of a plastic quad flat package (PQFP) was investigated. It was suggested that low temperature and longer molding time or high temperature and shorter molding time would result in less warpage. They also showed that the viscoelastic model predicted the warpage more accurately than the thermoelastic model.

Ernst et al.[3] proposed a cure-dependent model for mechanical modeling of stress evolution induced during cure in a particle-filled electronic packaging polymer. The constitutive relation can be written as a cure-dependent hereditary integral form as follows:

Correspondence to: D. Y. Gui (dygui@szu.edu.cn).

© 2008 Wiley Periodicals, Inc.

$$\sigma_{ij}(t) = \int_{\xi=-\infty}^{t} [2G[T(\xi),(t-\xi)] \cdot (\varepsilon^{d}_{ij,\xi})_{\xi} + K[T(\xi),(t-\xi)] \cdot (\varepsilon^{\text{eff}}_{v,\xi})_{\xi}]d\xi$$

where G = relaxation shear modulus function, K = relaxation bulk modulus function, σ^{d}_{ij} = deviatoric stress: $\sigma^{d}_{ij} = \sigma_{ij} - \sigma_{v} \cdot \delta_{ij}$, ε^{d}_{ij} = deviatoric strain: $\varepsilon^{d}_{ij} = \varepsilon_{ij} - \frac{1}{3}\varepsilon^{\text{eff}}_{v}$, $\varepsilon^{\text{eff}}_{v}$ = effective volumetric strain, and σ_{v} = volumetric stress.

Yang et al.[4] carried out finite element modeling for cure-induced warpage of plastic IC packages based on the aforementioned cure-dependent viscoelastic model and indicated that warpage induced during the curing process has significant contribution on the total warpage of the map.

Tarsha-Kurdi and Olivier[5] examined the effects of autoclave curing pressure and cooling rate on the room-temperature curvature of carbon/epoxy laminated strips. The results show that the room-temperature curvature of laminated strips seems to depend on the laminate initial in-plane dimension and is influenced by autoclave curing pressure. Huang and Tai[6] used the experimental design of Taguchi's method to determine the injection molding conditions and simulated the injection processes using the commercial software C-MOLD™. The results showed that the packing pressure had the greatest influence on the warpage, followed by mold temperature, melt temperature, and packing time.

Recent research has demonstrated that careful selection of processing parameters can dramatically reduce warpage suggesting that process modeling can be a powerful tool for determining optimal cure cycles.[7] But research of effects of molding pressure on viscoelastic behavior and mechanical properties of thermoset polymer used in IC packages have hardly been reported. The HVQFN package (Head-sink Very-thin Quad Flat Nonlead) is one of the latest developments in packaging technology because of its small size and excellent electrical performance. In this article, the manufacturing of typical map-chips encapsulated with filled epoxy resin under five pressure levels and the measurement of curvature of the packages after demolding and postcuring is described, respectively. The effects of molding pressure on the warpage of HVQFN packages is presented and discussed. The viscoelastic relaxation parameters of molding materials are obtained by using dynamic mechanical analysis (DMA). The characterization of the evolution of equilibrium moduli is analyzed for future modification of the model.

EXPERIMENTAL

Materials and sample preparation

The epoxy resin used as matrix material in this study was Novolac epoxy (EPN 1180) from Vantico (Switzerland), with an equivalent weight of epoxy groups equal to 175–182 g/equiv. Bisphenol-A was used as hardener, which has an equivalent epoxy weight of 114.1 g/equiv, and triphenylphosphine (TPP) as a catalyst. The Novolac epoxy and the hardener were mixed in a stoichiometric ratio of 1 : 1. Fused silica spheres (FB-940), from Denko, were used as filler. The filler had a median diameter of 15 μm with a density of 2.20 g/cm^3.

Epoxy resin and hardener were well mixed at 150°C and then cooled down to 85°C, and the catalyst was added and fully stirred. Afterward, the mixture was degassed at 75°C for about 20 min. To make a particle-filled composite, a certain amount of filler was added to the matrix resin, and they were well mixed in a special mixer (Kenwood, K-beater). According to previous research,[4] 65 wt % filler was used for this study. Then, the mixture was immediately cooled down and stored in a refrigerator at −15°C. Later, it was used to make round shape tablets for molding experiments.

The HVQFN package is a plastic-encapsulated chip scale package (CSP) with lead frame on the bottom of the package. It is usually manufactured by a so-called map-mold technology. The molding experiments were performed by a transfer molding process at Philips Semiconductors with a LAUFFER machine. HVQFN packages with two maps with 0.25-mm thick dies were made under different pressure levels (1.8, 3.6, 6.5, 8.66, 12.27 MPa, respectively), 140°C of molding temperature and about 5 min hold time. One map was just compound for the materials characterization and the other one was leadframe with chips glued on it for the curvature measurements.

The DSC measurements were performed in a DSC2920 differential scanning calorimeter of TA Instruments scanned at a heating rate of 10°C/min to 150°C to determine the glass transition temperature (and thus the demolding conversion).

At each experimental condition three products were molded. Then, the packages were immediately cooled down and stored in a refrigerator. The curvature measurements and viscoelastic tests were carried out after demold and after postcure, respectively. An example of a HVQFN package is shown in Figures 1 and 2.

Experimental techniques

The product shape (curvature) was measured after demold at 80% degree of cure (and cool down).

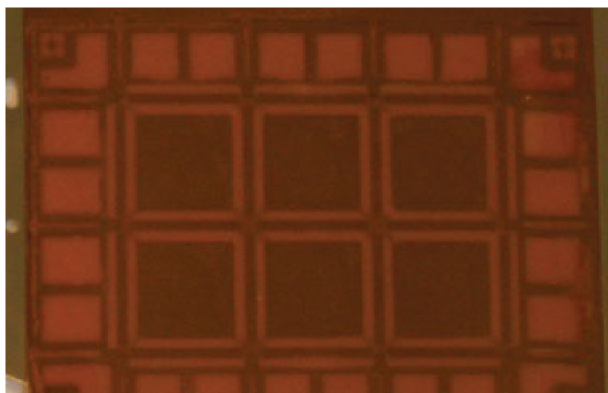

Figure 1 Bottom view of HVQFN package. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Next the packages were postcured for 1 h at 200°C (without any dead weight loading). After cooling down, the product shape was remeasured. The amount of warpage was determined from measurements of the surface shape using the setup shown in Figure 3. For the horizontal x and y displacements an Isel programmable precision XYZ-table was used which is equipped with 1-μm accurate stepper motors. The vertical coordinate was measured with a LVDT sensor. The top and bottom sides of the packages were probed by the LVDT. The curvature values were the average of measurements on top and bottom sides. In this way, the sagging effects due to the LVDT weight and gravity were eliminated.

DMA was used to get relaxation moduli curves of the molding compounds and to determine the stiffness coefficients E_n and the shift factors for temperature and pressure effects. Tensile DMA tests were performed by using a Metravib Viscoanalyzer VA4000. Continuous frequency sweeps were used for probing the viscoelastic properties. Several logarithmically spaced frequencies between 0.1 and 31.6 Hz were applied.

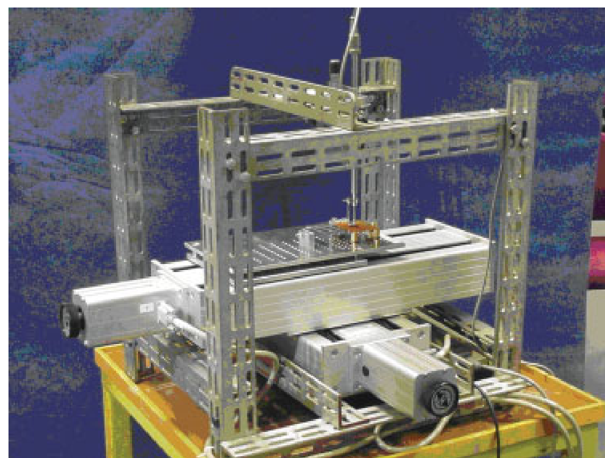

Figure 3 Overview of curvature measurement setup. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The temperature effect on the relaxation behavior was measured by using the conventional way of determining the viscoelastic properties. Frequency sweeps were applied at each temperature level. Figure 4 shows the strip DMA test. The dimensions of the test strip were about 40 × 8 × 0.9 mm^3.

RESULTS AND DISCUSSION

Characterization of materials properties

According to the viscoelastic model as proposed in Ref. 3, shear and bulk relaxation moduli should be obtained for modeling the stress state and warpage of the HVQFN package during processing. In this study, the pressure influence on the viscoelastic

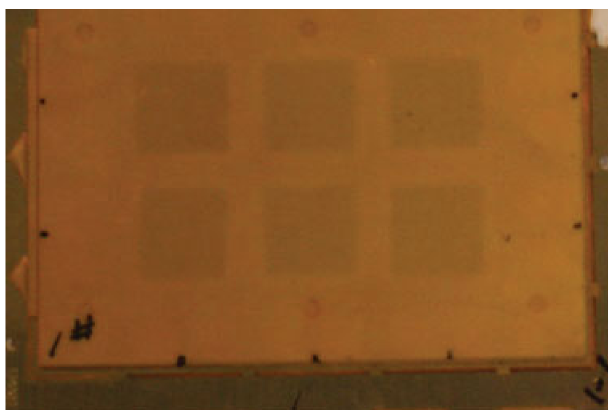

Figure 2 Top view of HVQFN package. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

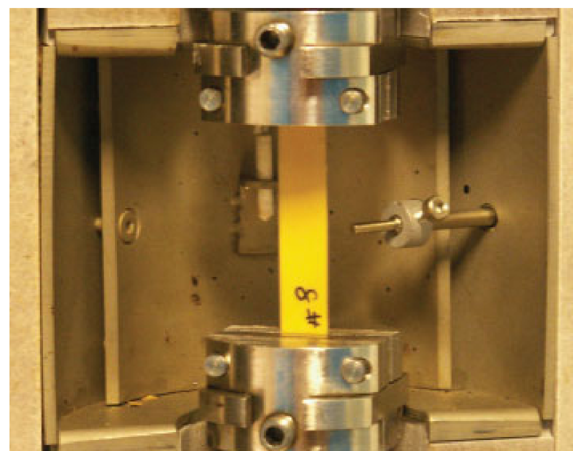

Figure 4 Longitudinal DMA testing. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

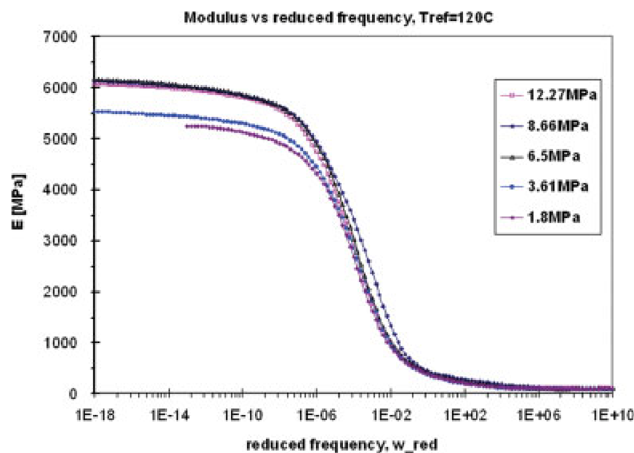

Figure 5 Typical master curves of tensile modulus versus reduced frequency for fully cured 65% filled epoxy resins, for different molding pressures (ref. temp 120°C). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

behavior of the applied molding compounds was considered by characterizing the tensile relaxation modulus, because of its accurate attainability and the interrelationship with the shear and bulk moduli.

The interrelations between bulk- and shear-relaxation modulus functions and the Young's modulus (tensile relaxation modulus, E) function can be formulated through Laplace transform relations of these property functions:

$$s \cdot \overline{E}(s) = \frac{9s \cdot \overline{G}(s) \cdot \overline{K}(s)}{\overline{G}(s) + 3\overline{K}(s)}$$

According to the time–temperature superposition principle,[8] the individual isothermal curves could be shifted along the frequency axis to form a single overlapping mastercurve. Figure 5 presents the typical master curves of moduli of the fully cured material under various molding pressures versus reduced frequency after being shifted along the frequency axis with reference temperature of 120°C, the glass transition temperature of the fully cured material. Figure 6 shows the attained temperature shift factor curves for different molding pressures. The pressure dependencies of the glassy moduli and rubbery moduli with error bars are shown in Figure 7. The error bars are results from the calculation of standard deviation of samples under each molding pressure level.

It can be seen from Figures 5 and 7 that the rubbery modulus values are among 96–108 MPa, almost constant for all the pressure levels. Figure 6 shows that shift factor curves are almost identical for all pressures. On the other hand, the glassy moduli have greater changes with the molding pressure. The glassy modulus has a lowest value (5263 MPa) at 1.8 MPa of molding pressure level and increases with the pressure and attains the maximum (6315 MPa) at the medium molding pressure level (8.66 MPa), and then decreases to a lower value (5817 MPa) at 12.27 MPa of molding pressure. This means that molding pressure has a significant effect on the glassy modulus of filled epoxy resins. This will probably have influence on the mechanical behavior of HVQFN packages.

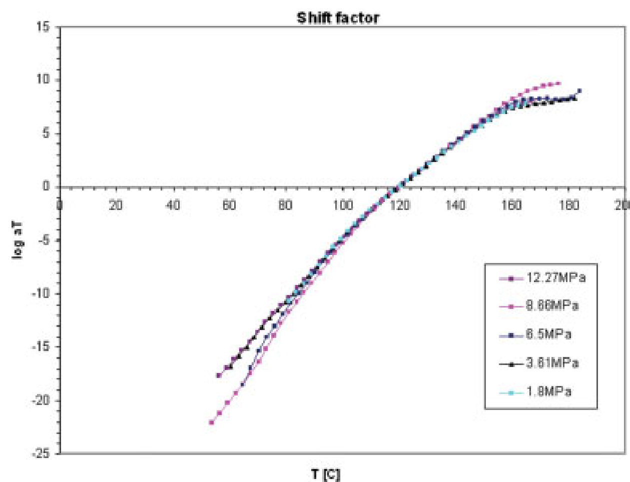

Figure 6 Typical temperature shift factor for different molding pressure (ref. temp 120°C). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Warpage of HVQFN packages

The shape was scanned along the HVQFN central lines, i.e., X1, X2, X3, and Y1, Y2 (Fig. 8). The origin of the coordinate system was fixed at the corner of the HVQFN samples. An example of the shape picture from Matlab program is shown in Figures 9 and 10. The full lines are measured coordinates and

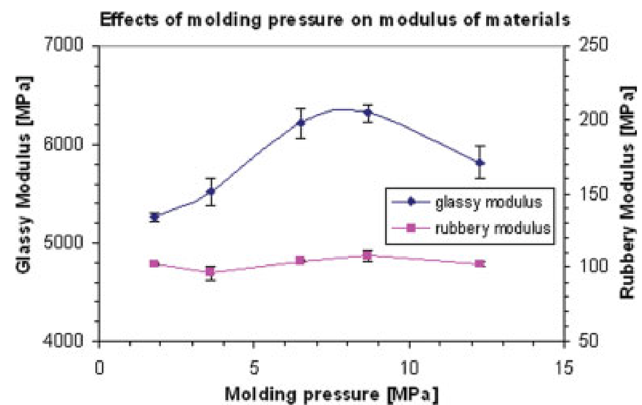

Figure 7 Average glassy and rubbery tensile modulus of fully cured materials verse molding pressure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

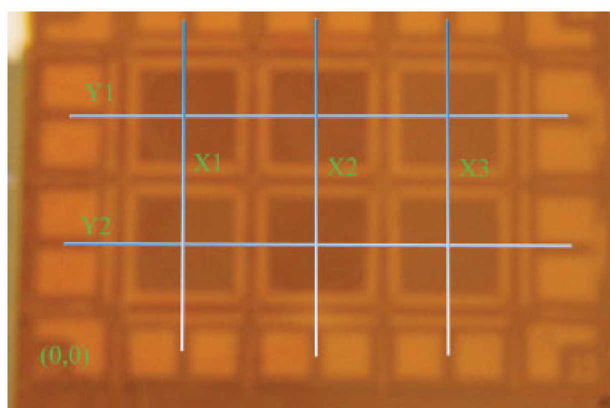

Figure 8 Schematic view of scan lines on HVQFN package. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

dashed lines correspond to a curved surface fit (i.e., a quadratic fit). Two measures for the average warpage were used in this study.

1. First of all a quadratic fit in two dimensions was applied to the data. This resulted into curvatures in x and y direction as well as a twist,

$$h(x,y) = c_0 + c_1x + c_2y + c_3xy + c_4x^2 + c_5y^2$$

$$\kappa_x \cong \frac{\partial^2 h}{\partial x^2} = 2c_4,$$

$$\kappa_y \cong \frac{\partial^2 h}{\partial y^2} = 2c_5,$$

$$\kappa_{xy} \cong \frac{\partial^2 h}{\partial x \partial y} = c_3.$$

   As a warpage measure, the maximum of κ_x and κ_y is taken.
2. The second way of characterizing warpage was by fitting a plane to the data, subtract this plane from the data and determine the difference between the highest and lowest points.

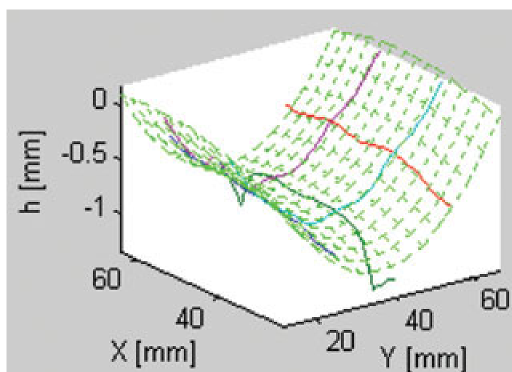

Figure 9 Top shape of postcured HVQFN package. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

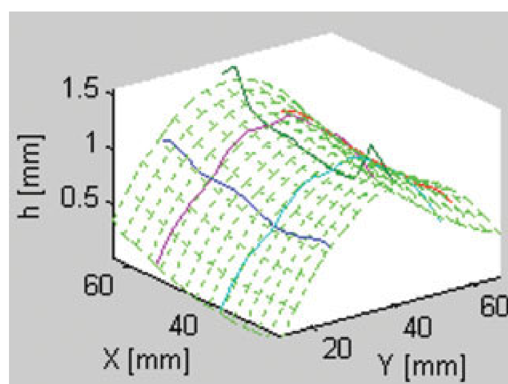

Figure 10 Bottom shape of postcured HVQFN package. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The average warpage results of samples versus molding pressure are shown in Figures 11 and 12.

Figure 11 shows warpage graphs according to the max (κ_x, κ_y) warpage criterion, and Figure 12 shows the graphs where the deviations from the average plane were used as a warpage measure. It can be seen that both the measures gave similar trends in most cases and it is in fact possible to find an average conversion factor which transforms one measure to the other (the factor, the max–min value divided by the max curvature value, is about 0.4 mm × 0.5 m for postcured samples).

The curvature directly after demold (dashed lines) is always much lower than postcuring (factor about 0.5). This cannot be explained by just thermal shrinkage during cooling down when assuming a stress-free state at start of cooling, since these shrinkages are of the same order of magnitude. The difference

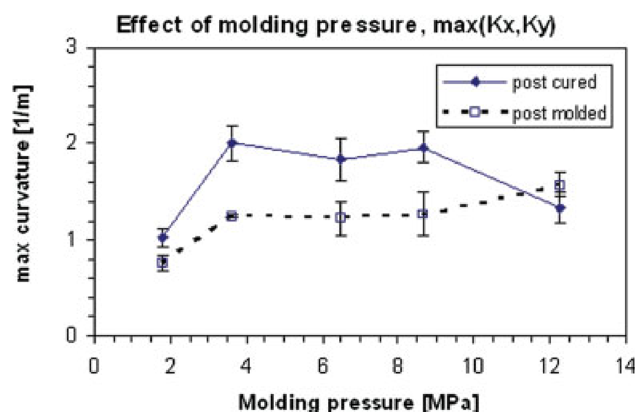

Figure 11 Measured warpage after demold (dashed lines) and after postcuring (full lines) according to criterion 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

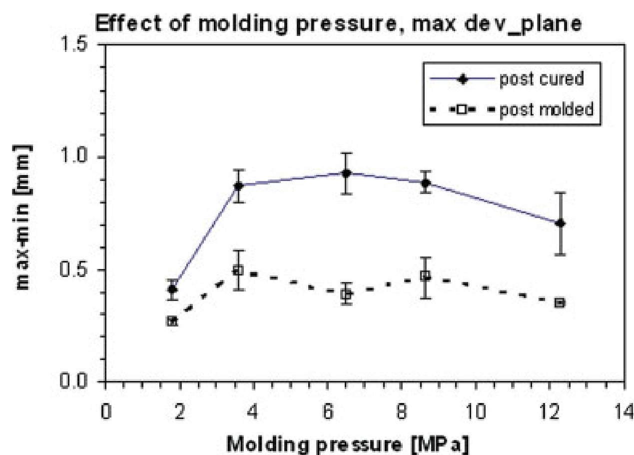

Figure 12 Measured warpage after demold (dashed lines) and after postcuring (full lines) according to criterion 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

in warpage is possibly due to the faster stress relaxation in the postmolded sample.

The curves show that molding pressure has apparent effects on the warpage of postcured packages. It can be noticed that warpage of the package is on a lower level for both lower and higher molding pressures. For example, the max curvature of HVQFN at 12.27 MPa molding pressure is 45% less than the average max curvature at 3.6–8.66 MPa. But some visible voids have been found in the package when the molding pressure decreased to 0.36 MPa in our experiment. So the molding pressure should be high enough to avoid more voids and mold-ejection difficulties.

The changes of warpage in the mold materials with molding pressure can be attributed to the following reasons:

Thermal expansion and shrinkage

Warpage is related to the phenomenon of material shrinkage. The thermal expansion and curing shrinkage occur during the molding process of thermoset polymers. This shrinkage/expansion results into stresses and deformations. The residual stress field is merely due to the chemical shrinkage and simultaneous stiffness built-up in packaging polymers during the curing process and afterward the cooling down phase.[3] The levels of processing-induced stress can seriously influence the stress fields under operating conditions and thus affect the critical states of stress and deformation.

When injection pressure and holding pressure increases, the effect on shrinkage decreases.

Void content

It is well-known from literature that the strength of composites decreases significantly with increasing void content.[9] Other properties also depend on the void content, e.g., stiffness and thermal expansion, which can be shown through micromechanics. This means that the shape distortion is likely to be affected by variations in void content.

Normally, some voids can be formed in a product during the molding process. The void content, size, and distribution depends on the filler volume fraction, resin properties, processing method, and processing conditions such as temperature, pressure, time, etc. Higher pressure can help reduce the content of voids in the product during molding.

Relaxation

Pressure slows down the relaxation behavior. The higher the pressure the more will be the ''solid like'' response, because a higher pressure decreases the free volume and thus hinders the movement of chain segments and thus causes more residual stress in molded packages and/or more serious warpage.

Therefore, the first two factors and the latter have reverse effects on the warpage of molded packages with increase of pressure. This means that final warpage is a result of competing effects. At lower pressure level, the relaxation probably is fast enough and has a predominant effect, although there occurs more shrinkage and voids in the materials. At higher pressure level, the decrease of shrinkage and voids has important effects, although there is less relaxation in the package. The molding pressure should be high enough to compensate for shrinkage and to avoid voids, but should be low enough to avoid overpacking, which can lead to high levels of residual stress and ejection difficulties.

From the experimental results as aforementioned, the molding pressure has some influences on the glassy Young's modulus and has little effects on the rubbery modulus and relaxation time of the fully cured package materials. The relaxation modulus amplitude is subtraction of rubbery modulus from glassy modulus. According to viscoelastic theory and the constitutive relation of particulate-filled polymer composites, the stress/strain evolution can be described as a function of the relaxation modulus amplitude so that the change in glassy modulus shown in Figure 6 as a function of molding pressure is correlated with the postcured curvature of the samples shown in Figures 9 and 10.

With material parameters and tensile and bulk viscoelastic relaxation parameters, mechanical behavior of HVQFN can be modeled based on a suitable process-dependent micromechanical model.[3] In this study, the DMA tests with Metravib show that the molding pressure factor has influence only on the relaxation modulus amplitude. This makes it easy to

take pressure into account for the mechanical modeling of HVQFN packages. Therefore, the previously developed temperature-cure-dependent model can be modified by including a pressure term in the relaxation amplitudes of future versions of the model.

CONCLUSIONS

HVQFN packages were manufactured under five molding pressure levels. The viscoelastic properties of the materials were characterized by using DMA analysis. The evolutions of warpage of the packages with molding pressure are described. The research results in this article provide a good basis for modification of the previously developed cure-temperature dependent viscoelastic model for molding pressure effects, such that improved modeling of the warpage of HVQFN packages will become possible.

Following conclusions can be made:

1. The molding pressure has significant effects on the warpage of both demolded and postcured packages. The curvature of HVQFN package at both lower (1.8 MPa) and higher molding pressures (12.27 MPa) is about 45% less than the average max curvature at 3.6–8.66 MPa. Optimal design considering molding pressure is needed.
2. The molding pressure has obvious influences on the glassy Young's modulus but has little effects on the rubbery modulus and relaxation time of the package materials. The trend observed in glassy modulus evolution with molding pressure is equivalent to the trend observed in the warpage evolution.

The authors acknowledge J.A.S. van Driel and J.C. Sterk for their technical assistance. They also thank Vantico Ltd. and Denka E and F Div. for the supply of epoxy resin and the silica fillers, respectively.

References

1. Kelly, G. In Proceedings of the 44th ECTC, IEEE, Washington, DC, 1994; p 102.
2. Yeung, D. T. S.; Yuen, M. M. F. J Electron Packaging 2001, 123, 265.
3. Ernst, L. J; van't Hof, C.; Yang, D. G.; Kiasat, M. S.; Zhang, G. Q.; Bressers, H. J. L.; Caers, J. F. J; den Boer, A. W. J; Janssen, J. ASME J Electron Packaging 2002, 124, 97.
4. Yang, D. G.; Jansen, K. M. B.; Ernst, L. J.; Zhang, G. Q.; van Driel, W. D.; Bressers, H. J. L.; Fan, X. J. In 2004 Electronic Components and Technology Conference, IEEE, Las Vegas, NV, 2004; p 98.
5. Tarsha-Kurdi, K. E.; Olivier, P. Composites Sci Technol 2002, 62, 559.
6. Huang, M. C.; Tai, C. C. J Mater Process Technol 2001, 110, 1.
7. O'Brien, D. J.; Mather, P. T.; White, S. R. J Compos Mater 2001, 35, 883.
8. Ferry, J. D. The Viscoelastic Properties of Polymer; Wiley: New York, 1980; p 264.
9. Svanberg, J. M. PhD Thesis, Lulea University of Technology, Lulea, Sweden, 2002.