Behaviors of QFN Packages on a Leadframe Strip

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Abstract

To lower the manufacturing cost of quad flat no-lead (QFN) packages, the number of QFN packages on a leadframe must be increased. However, the increased number of packages or changes to the layout of QFN packages on the leadframe can impact the mold compound flow behavior, which will, in turn, affect warpage, and the generation of voids inside the mold compound. In this paper, both simulation and experimental approaches were conducted to study the behaviors of QFN packages on a leadframe strip. For simulation, we will demonstrate and present an analysis methodology to account for the in-line processing parameters, especially the step of manufacturing and processing the mold compound material to form the QFN packages on a leadframe strip. The in-line manufacturing parameters, such as pressure, temperature, shrinkage, and processing timing, were all considered and modeled. A commercial finite element tool was used. For the experiment, we measured the warpages and the voids of QFN packages as a function of the package location on the leadframe. The warpage of the package, and the voids generation of QFN packages at different locations on the leadframe strip were studied. In conclusion, the experiment vs. modeling data was correlated, and the study proved to be very useful for the prediction of warpage, and void generations.

Key words

FEM, Mold Compound, QFN

I. Introduction

The quad flat no-lead (QFN) package offers a variety of benefits including reduced lead inductance, small size, thin profile, and low weight. It also uses perimeter input/output (I/O) pads to ease printed circuit board (PCB) trace routing, and the exposed copper die-pad technology offers good thermal and electrical performance. These features make the QFN an ideal choice for many applications where size, weight, and thermal and electrical performance are important. Fig. 1 illustrates some single and dual row QFN packages.

In this paper, the reliability of QFN packages was studied, including the warpage and the voids, especially from the manufacturing aspect. An integrated circuit (IC) encapsulation Finite Element Method (FEM) code was used to model the mold compound manufacturing processes. In additional to simulation, experiments of shadow moire and C-Mode Scanning Acoustic Microscopy (C-SAM) were conducted to collect data on the warpage and air traps of QFN packages which was then correlated with simulation data. The driving force of the work was to provide a design methodology to manufacture higher density QFN devices on the leadframe so as to lower the manufacturing cost.

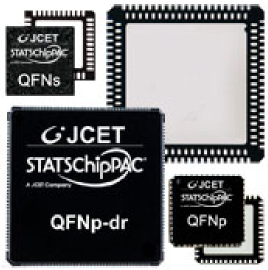

Fig. 1 Example of single and dual-row QFN packages

II. Rheokinetic characteristic of mold compound material

Mold materials used on QFN packages are ubiquitous. Their manufacturability as well as reliability have been proven through field applications over several years. However, the impact of mold compound materials during the manufacturing process and on the reliability of packages, such as warpage and voids, are not yet clearly understood [1]-[3].

In the current transfer molding process, flow and heat transfer are dynamically coupled with the curing reaction. The kinetics of the curing reaction not only affects the degree of conversion of the molding compound, it also has a strong relationship to the mold flow with an increase in viscosity due to the curing reaction. Viscosity is also influenced primarily by temperature and shear rate. Therefore, the rheological behavior of molding compounds is important for numerical modeling of the molding process [4]-[5].

To characterize the rheokinetic behaviors of mold compound material properties, viscosity, curing kinetics, and thermal conductivity were measured. The Cross-Exponential Macosko model was used to define viscosity behaviors and Kamel's model was used to predict the curing behavior of molded underfill (MUF) thermoset material.

The curing kinetic properties were measured using the Differential Scanning Calorimetry (DSC) method with different temperature ramp-up rates of 5, 10, and 20 °C/min. The experimental data of cure conversions were fitted by numerical parameters using the following Kamal's cure models. The fitting parameters are shown in Table I.

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

$$k_1 = A_1 \exp\left(-\frac{E_1}{T}\right) \qquad (2)$$

$$k_2 = A_2 \exp\left(-\frac{E_2}{T}\right) \qquad (3)$$

Table I. Numerical fitting parameters for Kamel's cure model of mold compound material

Fitting parameters	Unit	Constant
m	-	0.257
n	-	1.193
A1	1/sec	0.135
A2	1/sec	9.54e5
E1	K	15000
E2	K	7820

Where α is the degree of cure (0-1), T is temperature (K), t is time (sec), and m, n, A1, A2, E1 and E2 are numerical parameters constants. The viscosity, as a function of temperature and shear rate, was measured. The Cross-Exponential Macosko model was used to describe the behavior of viscosity and the fitting parameters shown in Table II.

$$\eta(\alpha, T, \dot{\gamma}) = \frac{\eta_0(T)}{1+\left(\frac{\eta_0(T)\dot{\gamma}}{\tau^*}\right)^{1-n}} \left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^{(C_1+C_2\alpha)} \qquad (4)$$

$$\eta_0(T) = B\exp(T_b / T) \qquad (5)$$

Where η is the viscosity (Pa-sec.), $\dot{\gamma}$ is the shear rate (1/sec.), T is the temperature (deg K), α is the degree of cure (0 - 1), and n, τ^*, B, T_b, C_1, C_2, α_g are data-fitted coefficients.

Table II. Numerical fitting parameters for Cross-Exponential Macoskco viscosity model of mold compound material

Fitting parameters	Unit	Constant
n	-	0.84
Tau*	Pa	0.000912
B	Pa-s	0.00248
Tb	K	4050
C1	-	25.8
C2	-	-11.7
αg	-	0.4

Fig. 2 shows the viscosity vs. shear rate of the mold compound material at different temperatures. The higher the temperature, the lower the viscosity of the mold compound material occurred. The graph indicates that the higher mold cavity temperatures may fill the cavity faster than at low temperatures. Thus, the mold cavity temperature needs to be chosen carefully in the molding process.

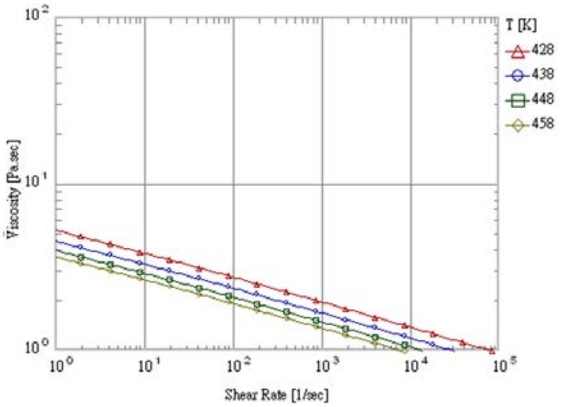

Fig. 2 Viscosity vs. shear rate of mold compound material at different temperatures

III. QFN devices on leadframe

In this study, the behaviors of QFN packages on a leadframe strip, as shown in Fig. 3, were studied. The mold compound pallets were placed at seven circular cull blocks then they were heated, melted, and injected into the runners at the top and bottom. Each cull block was responsible for two rows of QFN packages at the top, and two rows of QFN packages at bottom, as shown in Fig. 3.

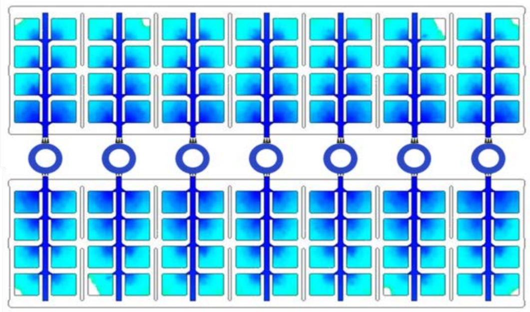

Fig. 3 QFN package array on a leadframe strip

After the fill, pack, and cure steps, the QFN packages were cut into individual components. The behaviors of QFN packages, such as warpage and voiding, will be dependent on where the devices are located on the leadframe. In this regard, the experimental data of warpage and voiding of the four rows of QFN packages on the leadframe were collected, as shown in Fig. 4. The first row is near the mold compound injection entrance and the fourth row is the final end of mold compound flow.

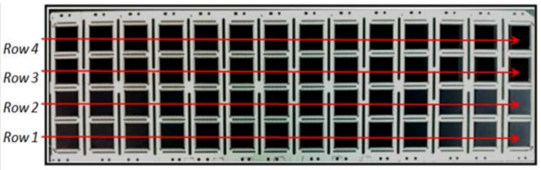

Fig. 4 QFN devices on a leadframe

The QFN packages were separated by stress releasing slots. Thus, after manufacturing the QFN strip and before the singulation of QFN packages, the entire leadframe may buckle randomly without a certain shape because the warpage of the entire leadframe strip is strongly dependent on how the leadframe is manually handled. Holding the leadframe at one corner or at the center with one hand will induce different buckling behaviors. However, what is important is that the intrinsic behaviors of QFN packages will be dependent on the processing factors, and the intrinsic properties of QFN packages will reside in the packages after the singulation.

IV. FEM Modeling

In this study, the FEM numerical simulation was used to predict warpage and the risks of potential voids as a function of QFN locations. The numerical simulation is an economic approach to avoid costly tests and to predict the reliability of IC packages before volume manufacturing. Fig. 5 illustrates a simplified computer-aided design (CAD) model which considers only one row of QFN packages and one half of primary mold compound flowing passage, also known as the runner, using a symmetrical boundary condition. The mold compound flows into the runner then from the runner into each QFN package. The QFN packages have very complex lead fingers and the simplified model is to capture the physics of molding processes without the need to model the entire leadframe so as to avoid costly computational time and resources. In this simulation, the detailed features of cull block were not modeled because the volume was very small compared with the rest of the mold compound volume inside the runner and QFN packages.

To correctly model the mold compound flow into the packages, the flow rate or flow speed as a function of time must be accurately calculated. In this regard, the molding machine's stroke position as a function of time was recorded as shown in Fig. 6. With the known mold compound's pallet size, the flow rate is calculated and thus the FEM model implements the flow rate based on the real processing parameters.

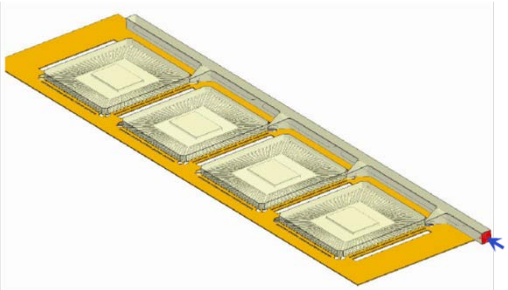

Fig. 5 One row of QFN packages and one half or runner on a leadframe strip

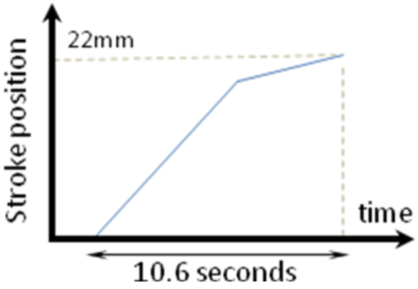

Fig. 6 Experimental stroke position as a function of time

V. Filling of mold compound

Fig. 7 illustrates the filling percentage of the QFN packages as a function of time. The mold compound enters each package from the bottom right corners and finishes at the top left corners. The red color of the first row is the initial filling time and the blue color is the final filling time which is located at the last row of QFN packages. Fig. 8 shows the potential risk of voids on the QFN packages. All the simulated potential voids appear at the edge of packages, thus they are not causing real risks. Fig. 9 shows the experimental CSAM images and there are no voids present.

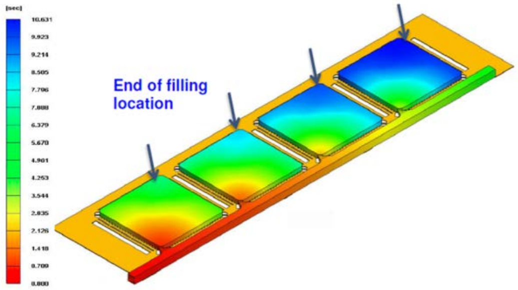

Fig. 7 Filling of mold compound on one row of QFN packages

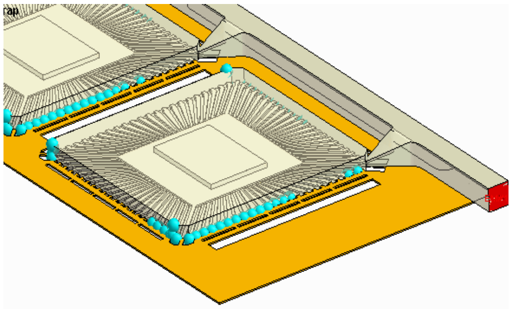

Fig. 8.Simulated potential air traps of the QFN packages

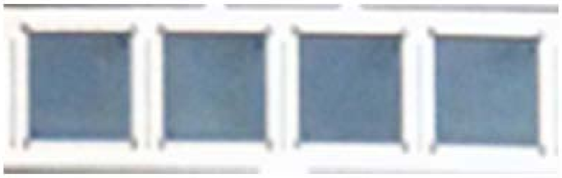

Fig. 9 C-SAM images of the QFN devices.

Fig. 10 illustrates the pressure at the mold compound entrance location as a function of time during the filling step. The pressure starts building up gradually after mold compound flows onto the runner and QFN devices. The first pressure jump occurs at the time when the first QFN package is fully filled. Similarly, the second and third jumps occur at the times when the second and third rows of QFN packages are fully filled. In between the first and second pressure jump, there is a small pressure variation which is due to the stoke velocity change. This indicates that there is a pressure gradient from the first row to the last row of QFN devices. Fig. 11, again, illustrates the variation of pressure at the entrance location during the curing step. The initial pressure fluctuation is due to that fact that the molding system is changing from a velocity control to pressure control scheme. After the fluctuation, the pressure holds at a constant value.

Fig. 12 and 13 illustrate the volume shrinkage rates of mold compound at the end of filling and curing steps. At the end of the filling step, most of the mold compound is only partially cured, and the first row of QFN, which is closer to the entrance, has a higher pressure, thus its shrinkage is lower. The last row of the QFN, which is away from entrance, has a lower pressure and therefore, has a higher shrinkage. After a much longer time at the curing step, the material at all locations is mostly cured and all QFN packages have about the same shrinkage rate. Similarly the volume shrinkage rate in Fig. 14 and 15 illustrates the percentage of conversion at the end of the filling and curing steps.

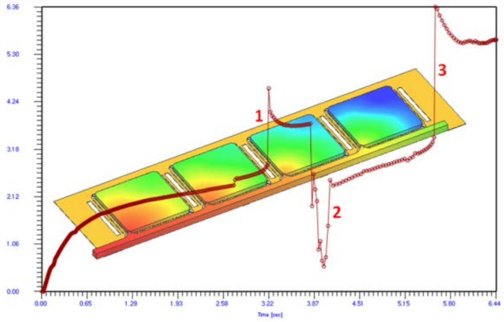

Fig. 10 Pressur at entrance location as a function time during the filling step

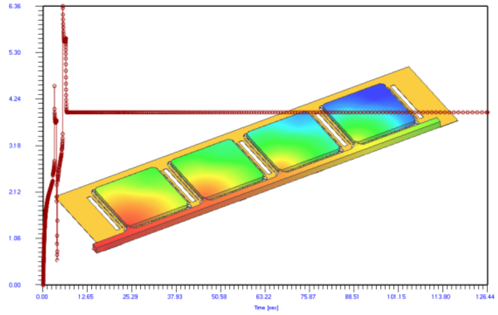

Fig. 11 Pressure at entrance location as a function time during the cure step

The differences of shrinkage rate and conversion percentage, as a function of time, in between rows of QFN packages and at different locations inside each QFN package are driving factors causing the variation of reliabilities among QFN packages.

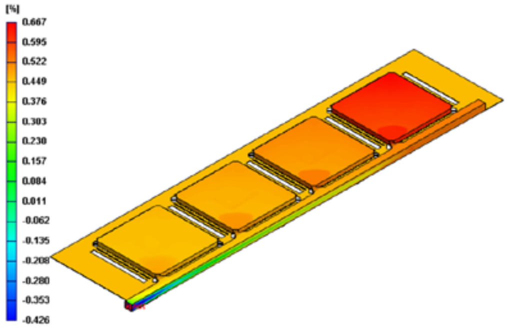

Fig. 12 Volume shrinkage rate (%) at the end of filling

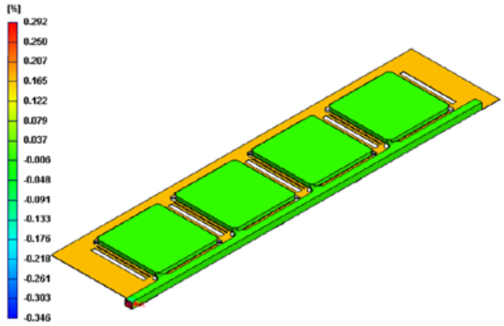

Fig. 13 Volume shrinkage rate (%) at the end of cure

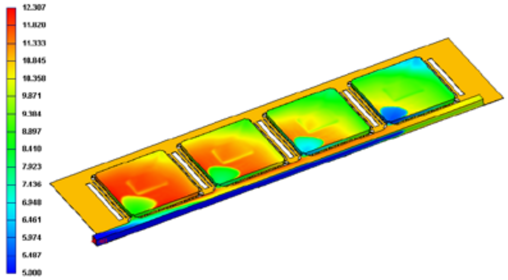

Fig. 14 Conversion percentage at the end of filling

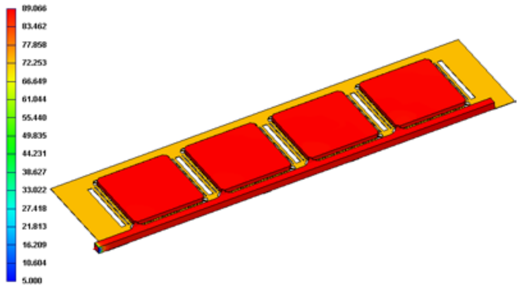

Fig. 15 Conversion percentage at the end of cure

VI. Experiment and Simulation of Warpage

Warpage of IC packages is one of the most important reliability issues and its behavior is very complex and difficult to predict because there are so many factors involved, such as the material properties, the configurations and dimensions, the temperature excursion range, the shrinkage, and the variations of manufacturing processes. For QFN warpage analysis, the traditional approach usually addresses the issue by considering the generic mechanical properties, such as the Young's modulus and the thermal expansion coefficient, and a temperature excursion range in order to calculate the thermally induced stresses inside the packages. In the consideration of temperature excursion, a reference temperature is usually used, and for most cases, the mold compound's melting temperature is usually assumed to be the reference temperature for which the mold compound is assumed to be at liquid state, thus it is stress-free. In this regard, the traditional mechanical approach does not consider the manufacturing processes and there are no differences among QFN packages on a leadframe because the same generic mechanical properties are used. Fig. 16 shows some measured warpage data of singulated QFN devices which were from different rows of the leadframe, and the warpage behavior could not be explained by traditional approach.

In this paper, the manufacturing parameters were considered in the analyses of warapge. After the filling and curing steps, QFN packages have different intrinsic stresses and different degrees of kinetic reactions accumulated inside the material. These intrinsic properties will impact the final warpage of QFN packages at room temperature. Fig. 17 shows the simulated warpage data vs. the averaged experimental data. The simulation data is referred to the warpage of QFN devices which are still on the leadframe and they are not yet being diced or singulated. The trend of both warpage data is similar and it shows that row 1 has lower warpage and row 4 has higher warpage, but there is a gap of warpage data in between the simulated and experimental data. Current simulation approach is not able to model the singulation procedure, thus we focused on the warpage of QFN packages while they are on the leadframe. The coupling of leadframe strip with QFN packages is probably one of the reasons causing the gap of experimental and simulated warpage data.

Fig. 18 uses the warpage data of the first row of QFN package, from simulation and experiment, as references, to compare the impact of rows or locations of packages on the warpage. The figure, in general, is able to capture the impacts of intrinsic properties of QFN packages at different locations. This set of data may be very important for the improvement of IC packages in the manufacturing because the ultimate manufacturing goal is to ensure all the IC packages to have the same physical behavior no matter where are the positions of IC packages located on the leadframe. An analysis approach, which is able to tell the differences of warpage data among IC packages on the leadframe, is definitely needed and this paper is doing so.

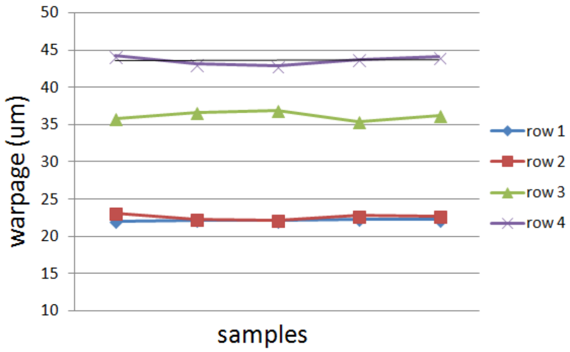

Fig. 16 Experimental warpage data of QFN packages

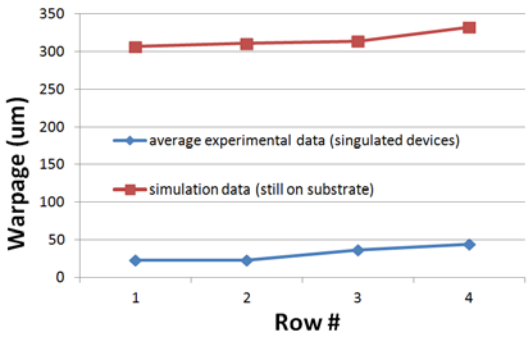

Fig. 17 Simulated vs. experimental data

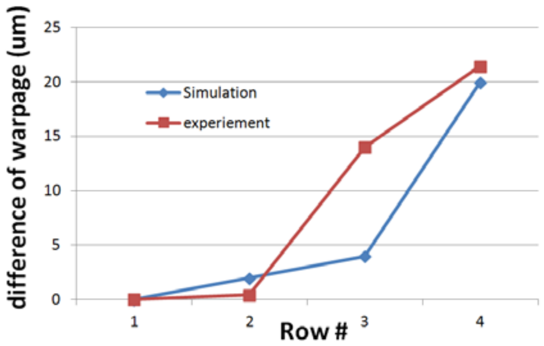

Fig. 18 Difference of warapge data with respect to first row of QFN package

VII. Conclusion and Future Works

In this paper, the behaviors of QFN packages, namely the voids and the warpage, were modeled, and simulation data was correlated with experimental data. With the results, we have concluded the following points: (1) the voids are at the edges of packages and they do not impose real risks; and (2) the warpage of singulated QFN packages is dependent on where are the packages are located. The packages closer to the mold compound flow entrance have less warpage while the packages away from the entrance have higher warpage.

We have demonstrated a good methodology for the prediction of the risks of the voids and warpage. The work is useful to help the industry improve the reliability of IC package manufacturing.

A simulation considering the processing parameters will be more reasonable in predicting the behaviors of IC packages because it considers the manufacturing factors. To better predict the reliability of QFN packages, work is still ongoing in a number of areas: (1) Current work considers the behaviors of packages on a leadframe after the fill, pack, and cure steps, but the post mold cure is not yet considered. An analysis including Post-Mold-Cure will be closer to the final real products for end customers. (2) The mold compound material may have visco-elastic and visco-plastic behaviors during the cooling step, which is from mold compound curing temperature to room temperature. A model including visco-elastic or visco-plastic models will be more accurate in predicting the warpage and stress behaviors. (3) There is only a QFN population pattern on the leadframe in this work. To lower the manufacturing cost, more QFN packages or a higher density of devices must be placed on the leadframe. Different layouts of QFN devices on the leadframe is worthy of analysis. (4) Warpage data of devices, before and after the singulation, is to be studied to know the impact of dicing.

IX. Acknowledgment

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X. References

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