Analysis of the Flow of Encapsulant During Underfill Encapsulation of Flip-Chips

Sejin Han and K. K. Wang

Abstract—In this paper, the flow of encapsulant during the underfill encapsulation of flip-chips has been studied. Analytical as well as numerical methods have been developed to analyze the flow. For capillary-driven encapsulation (by dispensing), the capillary force at the melt-front has been calculated based on a model for the melt-front shape. A model has also been developed for the analysis of forced-injection encapsulation. The numerical analysis uses a finite-element method based on a generalized Hele-Shaw method for solving the flow field.

Experiments have been performed to investigate the flow behavior using actual chips and encapsulants. Short-shot runs have been performed to observe the melt-front advancement at different flow times. In addition, measurements have been made of the material properties of the encapsulant, namely its viscosity, curing kinetics and surface-tension coefficient. The experimental and simulation results have been compared in terms of the flow-front shapes and times at different fill fractions. Such comparisons indicate that the model developed in this study is adequate to approximately simulate the flow during encapsulation of flip chips.

Index Terms—Dispensing, flip chip, injection, simulation, underfill encapsulation.

I. INTRODUCTION

T he use of flip chips has inherent advantages over other methods for high-density electronic packaging because it provides an area array which interconnects the chip and substrate [1]. The current process most commonly uses solder to connect the chip to the board. In that case, the difference in the thermal-expansion coefficients between the chip and the substrate can cause significant shear strain on the interconnects during temperature cycling, ultimately resulting in fatigue cracking and electrical failure [2]. This is particularly true as the size of the chip increases because the thermal stress in the interconnect increases with the distance from the neutral point of the chip. However, this problem can be significantly reduced by filling the space between the solder joints with encapsulant to provide mechanical reinforcement [2]–[5]. Because such encapsulation is provided mainly under the chip, it is called underfill encapsulation.

Currently, most flip chips are encapsulated by dispensing the encapsulant along the periphery of one or two sides of the chip. Capillary action (i.e., surface tension) drives the encapsulant through the space between the chip and the board. After filling is complete, the board is taken to an oven where it is cured. Because the current process fills the cavity (space between the chip and the board) by capillary action, it is very slow and could be incomplete, resulting in voids [6], [7]. The filling problem becomes even more serious as the chip size increases. Reference [8] has shown that the fill time is proportional to the square of the length of the chip. Such slow filling is detrimental to mass production. Substantial efforts are therefore being made toward speeding up the encapsulation process.

A pressurized underfill process can also be used for flip-chip encapsulation [9]. This process injects the encapsulant under pressure into the mold which surrounds and seals the chip. In this case, the flow is due to the pressure gradient from the inlet rather than the surface tension at the melt-front.

In either case, a flow analysis will help in developing an optimal encapsulation process or encapsulant. The objective of this study is to develop such an analytical/numerical capability for the underfill encapsulation process by either the capillary-driven or the pressurized-injection method.

Some experiments have been performed to verify the analysis results. Short-shot experiments either with the dispensing (capillary-driven) or injection process have been performed to compare with the flow behavior obtained from the analysis. Material-property measurements needed in the flow analysis have also been performed.

II. ANALYSIS

A. Analytical Solutions

If we treat the flow in the chip cavity as one-dimensional (neglecting complications from the solder in the cavity), Newtonian and isothermal, we can develop analytical solutions for the flow during the encapsulation process. The geometry for this problem is shown in Fig. 1, for which the pressure drop can be calculated from the following equation (for fully-developed channel flow)

$$\Delta p = \frac{12\eta VX}{h^2} = \frac{12\eta \left( \frac{dX}{dt} \right) X}{h^2}$$

(1)

where $\Delta p$ is the pressure drop from the flow entrance to the current location of the melt front $(X)$, $\eta$ is the viscosity of the fluid, $V$ is the average velocity, and $h$ is the gap thickness of the cavity.

In the case of encapsulation based upon the injection process, $\Delta p$ will be controlled by the injection mechanism. Typically, $\Delta p$ will be maintained constant or else varied in
order to maintain a constant flow rate. On the other hand, in the case of dispensing, the driving force is due to the surface tension at the melt front which is given by

\[ \Delta p = \frac{\sigma}{R} = \frac{\sigma \cos \theta}{h/2} \]  

(2)

where \( \sigma \) is the coefficient of surface tension, \( R \) is the radius of curvature of the melt front, and \( \theta \) is the contact angle.

If \( \Delta p \) (or \( \sigma \cos \theta \)) is constant in time, (1) can be solved for \( X \) to yield

\[ X = \left( \frac{\Delta ph^2}{6\eta} \right)^{1/2} = \left( \frac{\sigma h \cos \theta}{3\eta} \right)^{1/2} \sqrt{t} \]  

(3)

where \( t \) is the time measured from the start of the flow at the entrance. This equation shows that the advancement of melt front is proportional to the square root of time. This is consistent with the experimental results from [8], where the melt-advancement distance is measured versus time. From (3), we can calculate the fill time required to encapsulate a chip of length \( L \), namely

\[ t_{\text{fill}} = \frac{6\eta L^2}{\Delta ph^3} = \frac{3\eta L^2}{h \sigma h \cos \theta}. \]  

(4)

It can be seen from this equation that fill time is proportional to the square of chip length, proportional to the viscosity and inversely proportional to the pressure drop (or surface tension). Further, the fill time is inversely proportional to the square of cavity thickness in the injection case and inversely proportional to the cavity thickness in the dispensing case.

The above equation assumes that, for the dispensing case, the contact angle is constant (that is, the contact angle establishes an equilibrium value as soon as the encapsulant enters the gap in the chip and keeps that value throughout the flow). However, Schonhorn et al., [10] measured the contact angle versus time using several polymers on various substrates and found that the contact angle starts from some initial angle (typically close to \( 90^\circ \)) and slowly develops toward an equilibrium value. In particular, Newman [11] suggested the following equation to describe the time dependence of contact angle

\[ \cos \theta = \cos \theta_e (1 - a e^{-ct}) \]  

(5)

where

\[ a = 1 - \frac{\cos \theta_0}{\cos \theta_e} \]  

(6)

\[ c = \frac{\sigma}{\eta M} \]  

(7)

in which \( \theta \) is the contact angle at time \( t \), \( \theta_0 \) is the initial contact angle, \( \theta_e \) is the equilibrium contact angle, and \( M \) is a constant which depends on the surfaces in contact with the encapsulant. Using this time-dependent contact angle, the fill time can be calculated by

\[ t_{\text{fill}} = \frac{3\eta L^2}{h \sigma h \cos \theta} + \frac{a}{c} \left( 1 - e^{-ct_{\text{fill}}} \right) \]  

(8)

which has to be solved iteratively due to the nonlinear dependence on \( t_{\text{fill}} \).

In addition, the shear rate at the wall for Newtonian flow in a rectangular cavity can be calculated from the following equation (neglecting side walls and assuming constant flow rate)

\[ \gamma = \frac{\partial Q}{h^2 \omega} = \frac{6L}{h t_{\text{fill}}} \]  

(9)

where \( Q \) is the volumetric flow rate and \( \omega \) is the width of the rectangular cavity.

B. Numerical Analysis

For a rigorous and more accurate analysis (taking into account such complicating factors as non-Newtonian flow, nonisothermal effects and the existence of solder in the cavity), we need to employ a numerical simulation for the flow in the cavity. In current industrial practice, the particle size in the encapsulant (typically 20 \( \mu \text{m} \)) is not negligible compared to the cavity thickness (typically 100 \( \mu \text{m} \)). Therefore, it would be more accurate to model the physics in terms of suspension or granular flow [12] which, however, would greatly complicate the analysis when applied to the encapsulation process. As a compromise and simplifying approximation, we propose to use the following continuum approach based on viscosity measured under comparable flow conditions. In particular, if the thickness of the cavity is very small compared to the width, and the inertia effect is small compared to the viscous effect, we can use the Hele–Shaw approximation [13], [14]. This will be appropriate as long as the distance between adjacent solder locations is large compared to the cavity thickness. Under these assumptions, we obtain

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \]  

(10)

\[ 0 = \frac{\partial}{\partial z} \left( \eta \frac{\partial u}{\partial z} \right) - \frac{\partial p}{\partial x} \]  

(11)

\[ 0 = \frac{\partial}{\partial z} \left( \eta \frac{\partial v}{\partial z} \right) - \frac{\partial p}{\partial y} \]  

(12)

\[ \rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \frac{\partial T}{\partial t} + \frac{d\alpha}{\partial t} H \]  

(13)
where $u$, $v$, and $w$ are the velocity components in the $x$, $y$, and $z$ directions, respectively (where $z$ corresponds to the gap direction). Also, $p$ is the pressure, $T$ the temperature, and $\alpha$ the degree of cure. Further, $\rho$ is the density, $C_p$ the heat capacity, $k$ the thermal conductivity, and $H$ the heat generation due to curing. In the above equations, (10) is the continuity equation, (11) and (12) are the force balance in the $x$ and the $y$ directions, and (13) is the energy equation. These equations have to be solved together with a curing-kinetics equation. One example of such curing kinetics is that due to Kamal [15] which will be described later. The above equations are solved as in [14].

Together with the above equations, appropriate boundary conditions have to be used. In the case of capillary-driven flow, the boundary conditions on pressure will be

At the inlet:

$$p = p_{\text{atm}}$$  \hspace{1cm} (14)

At the melt-front:

$$p = p_{\text{atm}} - \frac{\sigma}{R} = p_{\text{atm}} - \frac{2\sigma \cos \theta}{h}$$  \hspace{1cm} (15)

where $p_{\text{atm}}$ is atmospheric pressure. In the above equation, $\cos \theta$ can be assumed to be constant or else variable as in (5). In the case of injection encapsulation, the driving force due to capillary force is typically negligible compared to that due to applied pressure, and the boundary conditions on pressure are

At the inlet:

$$p = p_{\text{inlet}} \text{(applied pressure)}$$  \hspace{1cm} (16)

At the melt-front:

$$p = p_{\text{atm}}.$$  \hspace{1cm} (17)

At the solid boundaries in the $x$–$y$ plane, the boundary condition on pressure will be

$$\frac{\partial p}{\partial n} = 0$$  \hspace{1cm} (18)

which corresponds to zero normal velocity (i.e., impermeable boundary). Boundary conditions on the temperature and degree of cure are given by prescribed values at the entrance. The mold wall is given a fixed temperature. No conditions at other boundaries will be enforced on the temperature or degree of cure.

III. EXPERIMENT

A. Material Characterization

Some material properties of the encapsulant are needed to analyze the flow. Material properties tested in this paper are viscosity, curing kinetics and surface tension. The encapsulant used in the present investigation is Hysol FP4510 from Dexter Corporation, Industry, CA.

1) Viscosity: The rheology of the encapsulant has been measured with a Rheometrics mechanical spectrometer (RMS) as a function of temperature, shear rate, degree of cure and gap thickness. Parallel plates with a diameter of 50 mm were used in the oscillatory mode. Because the cavity thickness between the chip and the board is very small (about 100 $\mu$m), the gap thickness in the rheological measurement should be comparable to the actual cavity thickness in the chip. The measured rheological results are shown in Fig. 2. Fig. 2(a) shows the viscosity dependence on shear rate at different temperatures. The gap thickness is 0.2 mm with maximum strain of 100%. The extended Cox–Merz relation [16] has been used to convert the dynamic viscosity to the steady-shear viscosity. This figure suggests that the material exhibits a yield stress at low shear rates and a power-law behavior at high shear rates. Therefore, the viscosity dependence on shear rate can be represented by [17]

$$\eta = \frac{\tau_y}{\gamma} + K \gamma^{n-1} = \left(\frac{K \tau^{n-1}}{1 - \frac{\tau_y}{\tau}}\right)^{1/n}$$  \hspace{1cm} (19)

where $\eta$ is the viscosity, $\gamma$ the shear rate, $\tau$ the shear stress, $\tau_y$ the yield stress, and $K$ & $n$ are curve-fitting parameters. The values of $\tau_y$ and $K$ at different temperatures are shown in Fig. 2(b) which have been obtained from Fig. 2(a). In turn,
Fig. 3. (a) Viscosity change when the sample is heated at 5 °C/min, starting at room temperature, with frequency of 25 rad/s and strain of 100% and (b) same plot as (a) but with the x-axis changed to degree of cure as described in text.

\[ \tau_y = \tau_{y0} \exp \left( \frac{T_y}{T} \right) \]  \hspace{1cm} (20)

\[ K = K_0 \exp \left[ \frac{-C_A(T - T_G)}{C_B + (T - T_G)} \right] \]  \hspace{1cm} (21)

where \( \tau_{y0}, T_y, K_0, T_G, C_A, \) and \( C_B \) are curve-fitting parameters. (The values for these various parameters are listed later in Table I.)

Fig. 3(a) shows the viscosity change with time when the temperature of the sample increases linearly with time at 5 °C/min, starting at room temperature. The shear rate used was 25 s\(^{-1}\). This figure shows an initial decrease in viscosity due to temperature rise until curing becomes important with corresponding rise in viscosity. The viscosity in Fig. 3(a) can be related to the degree of cure of the sample by using the curing-kinetics data measured by differential-scanning calorimetry as described below. The results thus obtained are shown in Fig. 3(b). In turn, the cure dependence of the

encapsulant viscosity can be fitted by the following equation due to Macosko [18]

\[ K_0 = K_{00} \left( \frac{\alpha_y}{\alpha_{y0}} - \alpha \right)^{(C_1 + C_2\alpha)} \]  \hspace{1cm} (22)

where \( \alpha \) is the degree of cure and \( K_{00}, \alpha_{y0}, C_1, C_2 \) are curve-fitting parameters.

Fig. 4(a) shows the viscosity measured with different gap thicknesses. These data were obtained at 27 °C and the gap thickness was varied between 0.15 and 0.4 mm. These results indicate that the viscosity decreases with decreasing gap thickness (it will increase again when the gap thickness approaches the particle size). Fig. 4(b) shows the viscosity at a fixed shear rate and temperature at different thicknesses obtained from Fig. 4(a). In turn, this suggests the following relation between viscosities measured at different thicknesses

\[ \eta_{\text{thickness}} = \eta_0 (A + B \log h) \]  \hspace{1cm} (23)

where \( \eta_0 \) is the viscosity at a reference thickness \( h_0 \) and \( A, B \) are constants. This equation should apply when the gap
thickness is larger than the filler size and smaller than some critical thickness (which is much larger than the filler size). When the gap thickness is larger than the critical thickness, the viscosity will be constant.

2) Curing Kinetics: The curing kinetics of the encapsulant have been determined using a Differential Scanning Calorimeter (DSC). Corresponding results are presented in Fig. 5 which shows the degree-of-cure of specimens measured under two different scanning rates (5 and 10 °C/min), starting at 40 °C. The results, in turn, have been fitted using [15]

\[
\frac{d\alpha}{dt} = (K_1 + K_2e^{E_1/T})(1 - \alpha)\gamma 
\]

(24)

\[
K_1 = A_1e^{(-E_1/T)}
\]

(25)

\[
K_2 = A_2e^{(-E_2/T)}. 
\]

(26)

Fig. 5. Curing kinetics of Hysol FP4510 at two different constant heating scanning rates, 5 and 10 °C/min.

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

![Graph](image5)

Fig. 6. (a) Contact angle and height of a drop on a substrate and (b) one example of measured profile of an encapsulant drop on a ceramic substrate.

3) Surface Tension: Surface-tension values were obtained by measuring the equilibrium shape of encapsulant droplets [see Fig. 6(a)]. In particular, a specimen of encapsulant was dropped on a substrate surface. Once the drop reached equilibrium shape, the drop was cured in order to solidify the shape. The profile of the drop was then determined by using a three-dimensional (3-D) measurement system. One example of such results is shown in Fig. 6(b). From this, the contact angle and the height of the drop can be measured. Such results are shown in Fig. 7 which corresponds to the case when the encapsulant (Hysol FP4510) is dropped on the ceramic surface. The measurements were done at different temperatures, as indicated.

The measured contact angles are shown in Fig. 7(a) from which it is seen that the contact angle decreases with increase in temperature. In turn, the contact angle can be fitted to the temperature by a second-order polynomial

\[
\theta = \theta_A + \theta_B T + \theta_CT^2. 
\]

(27)

Corresponding measurements of the height of the drop are also shown in Fig. 7(a). It is seen that the height also decreases with increasing temperature.
The surface tension of the drop can be calculated from the following equation using the measured height and contact angle \[1\]

\[
\sigma = \frac{\rho g H^2}{2(1 - \cos \theta)}
\]

(28)

where \(\rho\) is the density of the encapsulant, \(g\) is the gravitational constant of the earth, \(H\) is the height of the drop, and \(\theta\) is the contact angle. The surface tension thus obtained at different temperatures is shown in Fig. 7(b). In turn, the surface tension versus temperature can be fitted to

\[
\sigma = \sigma_0 \exp(\tilde{A} T)
\]

(29)

where \(\sigma_0\) and \(\tilde{A}\) are constants. The fitted result is shown as the dashed line in Fig. 7(b). Such measurements were also done on a silicon surface, with similar results. It is noted that the present encapsulation experiments were conducted with a chip on a ceramic substrate such that one side of the cavity is ceramic and the other side is silicon.

The resulting measured properties of Hysol FP4510 are summarized in Table I (where the constants for the surface tension are for the ceramic substrate).

### B. Encapsulation Experiment

Experiments have been performed to investigate the flow of encapsulant during the underfill encapsulation process. A chip from IBM has been used for this purpose, with the encapsulant being either dispensed or injected at the entrance. In the injection case, a special mold was made. In both cases, the encapsulation was conducted using the same grade material as in Section III-A. Such flow was stopped after a specified time. The chip was then placed in an oven at about 150 °C for 3 h to cure the encapsulant, after which the chip was ground off to inspect the encapsulation layer.

1) Dispensing Encapsulation:

a) Fill-Time Measurement: The fill-time measurements were conducted at various temperatures. In the actual experiment, dispensing was applied for a certain time after which all the encapsulant outside the chip cavity was removed. By examining the melt-front location after curing the encapsulated chip, the fraction of volume filled during the dispensing time was determined. The measured fill fraction of volume as a function of dispensing time is given in Table II.

b) Melt-Front Shapes: Fig. 8(a) shows the encapsulation layer when the encapsulant was dispensed at the central point of one edge of the chip (point gate). In this picture, the white circles correspond to the solder joints whereas the black area

is the encapsulated area. Although dispensed at one point, the melt-front is seen to be almost flat. Fig. 9(a) shows the melt front when the encapsulant is dispensed along one entire edge of the chip (edge gate). In this case, the melt-front in the central region is seen to lag behind the melt-front in the peripheral zone.

2) Pressurized Encapsulation: Figs. 10(a) and 11(a) show the encapsulation layer at different filling levels when the encapsulant was injected from the central point of one edge of the chip. By comparing Figs. 8(a) and 10(a), it can be seen that flow in the solder region is enhanced relative to the peripheral region in the injection case.

### IV. COMPARISON OF EXPERIMENTAL AND ANALYSIS RESULTS

Simulation of the encapsulation process has been performed using a code based on the methods described in Section II-B. Fig. 12 shows the geometric model and finite-element mesh used for the flow simulation of encapsulation of an IBM chip. Fig. 12(a) shows the geometric model where every solder insert in the cavity is exactly modeled. Note that there are 401 solders in the current chip. The length of the chip is about 7 mm, the thickness of the cavity is 0.1 mm, the solder diameter is about 0.16 mm and the clearance between adjacent solder joints is about 0.09 mm. Fig. 12(b) shows the finite-element mesh generated based upon this geometric model. Triangular elements have been used with a finer mesh near the solder joints because of the complicated geometry in that region. The total number of elements in this case is 7601 and the number of nodes is 4439. In the dispensing simulation, the contact angle at the melt front has been assumed to be either constant or else dynamic as given by (5). Curvature in the \(x-y\) plane has been neglected (that is, only the curvature in the thickness direction has been considered). For the injection case, a constant flow rate has been assumed.

The values of \(M\) and \(\theta_0\) for the dynamic-contact-angle case [in (6) and (7)] have been determined by comparing the simulated melt-front advancement and experimental melt-front advancement for one specific run (dispensing experiment at 23 °C). The values thus obtained are \(M = 17.1\) and \(\theta_0 = \)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dispensing time (s)</th>
<th>Fraction of volume filled</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>180</td>
<td>0.250</td>
</tr>
<tr>
<td>23</td>
<td>600</td>
<td>0.402</td>
</tr>
<tr>
<td>23</td>
<td>2700</td>
<td>0.646</td>
</tr>
<tr>
<td>50</td>
<td>180</td>
<td>0.676</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
<td>0.926</td>
</tr>
</tbody>
</table>

### TABLE I

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>(n)</th>
<th>(\eta) [Pa·s(^n)]</th>
<th>(C_A)</th>
<th>(C_B) (K)</th>
<th>(T_E) (K)</th>
<th>(T_C) (K)</th>
<th>(C_1)</th>
<th>(C_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.916</td>
<td>153.6</td>
<td>18.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.649</td>
<td>0.00138</td>
<td>2148.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE II

<table>
<thead>
<tr>
<th>Surface Tension</th>
<th>(\sigma_0) [N/m]</th>
<th>(\tilde{A}) (1/K)</th>
<th>(\sigma_0) (°)</th>
<th>(\theta_0) (°/K)</th>
<th>(\theta_0) (°/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1236</td>
<td>-3.80E-3</td>
<td>17.27</td>
<td>0.1760</td>
<td>-3.76E-4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curing Kinetics</th>
<th>(H) [J/kg]</th>
<th>(\mu)</th>
<th>(\nu)</th>
<th>(A_1) [1/s]</th>
<th>(A_2) [1/s]</th>
<th>(E_1) [K]</th>
<th>(E_2) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>95000</td>
<td>1.35</td>
<td>1.36</td>
<td>4.31E5</td>
<td>5.30E7</td>
<td>7.59E3</td>
<td>9.02E3</td>
<td></td>
</tr>
</tbody>
</table>

### Materials Properties Measured for Hysol FP4510 Relating to (19)–(27) and (29)

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>(T_{Cp})</th>
<th>(\mu)</th>
<th>(\nu)</th>
<th>(\lambda)</th>
<th>(\rho)</th>
<th>(\sigma_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.110</td>
<td>0.103</td>
<td></td>
<td>0.488</td>
<td>0.015</td>
<td>0.1760</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dispensing time (s)</th>
<th>Fraction of volume filled</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>180</td>
<td>0.250</td>
</tr>
<tr>
<td>23</td>
<td>600</td>
<td>0.402</td>
</tr>
<tr>
<td>23</td>
<td>2700</td>
<td>0.646</td>
</tr>
<tr>
<td>50</td>
<td>180</td>
<td>0.676</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
<td>0.926</td>
</tr>
</tbody>
</table>
1.48 radian (or 84.8°), which will be used for the analysis of other runs as well.

A. Fill-Time Comparison

Time to fill a certain volume fraction of the chip cavity has been calculated by various methods for the dispensing case. Table III compares the experimental and calculated fill times. In the table, “Analytic: Constant” means the fill time has been calculated using analytic equations with constant contact angle (4) whereas “Analytic: Dynamic” means the fill time has been calculated using analytic equations with dynamic contact angle (8). “Numerical: Constant” is when the fill time has been calculated using the numerical simulation with constant contact angle whereas “Numerical: Dynamic” is when the fill time has been calculated using the numerical simulation with dynamic contact angle. The same results as in Table III are shown in Fig. 13.

It is noted that the fill-time calculation using analytic equations has been performed in the following steps.
1) The contact angle and surface tension can be obtained from (27) and (29), respectively, for given temperature.
2) Estimate the fill time.
3) Using this fill time, the shear rate can be calculated from (9). With this shear rate and temperature, and assuming zero degree of cure, the viscosity can be obtained from (19)–(23).
4) With the surface tension obtained from step one and the viscosity obtained from step three, calculate the fill time using (4) for constant contact angle and (8) for dynamic contact angle.
5) With the newly obtained fill time, go back to step three and iterate steps three through five until convergence. In the above steps, for partial filling case, use \( fL \) instead of \( L \) (where \( f \) is the fill fraction).
As can be seen from the results in Table III (or Fig. 13), the dynamic-contact-angle assumption gives better results than the constant-contact-angle assumption. Also, numerical simulation results are better than the analytical solution results. Another point that can be noted from this fill-time experiment is that the fill time heavily depends on the temperature. For example, between 23 and 50 °C, the fill time changes by more than 15 times for a similar fill fraction. There are three factors that cause this. One is the temperature dependence of viscosity (viscosity increases with decreasing temperature). The second is the shear-rate dependence of viscosity. As the flow slows down with decreasing temperature, the shear rate decreases which causes further increase in viscosity. This dependence gets higher in the low-shear-rate range because of the yielding phenomenon. The third factor is the dependence of the dynamic-contact-angle development rate on temperature. As can be seen from (5)–(7), the dynamic-contact-angle development rate depends on the factor “c” which, in turn, depends upon both surface tension and viscosity. However, the viscosity changes more rapidly with temperature than the surface tension such that “c” decreases with decreasing temperature (because of the increase in viscosity) which causes a slower development of contact angle [as can be seen from (5)], making the flow even slower.

B. Melt-Front Shapes

Fig. 8(b) shows the predicted melt-front shape and velocity-distribution arrows when the encapsulant is dispensed from one point. Compared with the experimental melt-front shape shown in Fig. 8(a), which has the same fill fraction as Fig. 8(b), it is seen that the melt-front advancement in the solder region is slower in the experiment than in the simulation.
Fig. 12. (a) Geometric model of chip cavity and (b) finite-element mesh for flow simulation in the chip cavity.

Fig. 9(b) shows the predicted melt-front shape and the velocity distribution for the case when the dispensing is done along one entire edge of the chip. Comparison of the experimental melt front shown in Fig. 9(a) with this figure indicates that the melt-front advancement in the solder region is over-predicted in this case also.

Figs. 10(b) and 11(b) show predictions when the encapsulation is done by injection from the center of one cavity edge. These figures indicate the melt-front shape for different flow times. The predicted melt-front shape is seen to be in reasonably good agreement with the corresponding experimental melt-front shapes shown in Figs. 10(a) and 11(a).

Because the clearance between the solder inserts (0.09 mm) is comparable to the cavity thickness (0.1 mm), the pressure calculated from the Hele–Shaw approximation could be inaccurate, underestimating the flow resistance in the solder joints. However, the present results indicate that the Hele–Shaw approach can still give reasonable melt-front predictions for the injection case. The fact that the current simulation overpredicts the melt-front advancement in the solder region for the dispensing case may be due to an over-prediction in the simulation of the surface tension in the solder region. One possible reason for this is that the contact angle development in the solder region may be slower than in the unobstructed region. For accurate prediction of the surface tension in the solder region, it would be required to accurately calculate the curvature of the melt front in the planar and thickness directions. This would require a 3-D flow analysis; however, even if such an analysis were available, the complicated geometry of the solder inserts would require a huge number of elements, making the calculation intractable. Results from the current study indicate that the analysis methods developed in this study can be used to approximately analyze the flow during the underfill encapsulation process.

V. CONCLUSION

The following can be concluded from this study.

1) The viscosity of encapsulant for flip-chip encapsulation depends significantly on temperature, shear rate and degree of cure. It also depends on gap thickness to a lesser degree.

2) The surface tension of the encapsulant decreases slightly with increase in temperature.
3) Dynamic contact angle has to be used to analyze the flow of encapsulant under dispensing.

4) Hele–Shaw model can be used to approximately analyze the flow of encapsulant under dispensing or injection.

ACKNOWLEDGMENT

The authors appreciate the help of Dr. C. A. Hieber of Cornell University for helpful discussions, Dr. D. Farquhar and Dr. B. T. Han, IBM, for donating samples and useful discussions, and Dr. G. Westby and Dr. P. Borgesen, Universal Instruments, for their help in the experiment.

REFERENCES


Sejin Han received the B.S. and M.S. degrees from Seoul National University, Seoul, Korea in 1986 and 1988, respectively, and the Ph.D. degree from the Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, in 1994. He is now a Research Associate at Cornell University. His research interests are on the material processing and the semiconductor chip encapsulation including flip chip on board.

K. K. Wang received the Ph.D. degree from the University of Wisconsin, Madison. He is the Sibley Professor of Mechanical Engineering, Emeritus and Director of the Cornell Injection Molding Program, Cornell University, Ithaca, NY. Prior to his teaching career, he had 17 years of industrial experience in China, Japan, Germany, and the United States. From 1968 to 1970, he taught at the University of Wisconsin and then joined the Cornell faculty in 1970. His research interests span over a wide area of various manufacturing processes of metals and plastics. He has published more than 130 papers and is a co-inventor of the K-System, a patented thermal conductivity measuring device for polymers.

Dr. Wang has received many awards from ASME, SME, and AWS. He is a Fellow of ASME, SME, an Active Member of CIRP, and was elected to the National Academy of Engineering in 1989.