Underfill Flow as Viscous Flow Between Parallel Plates Driven by Capillary Action

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Abstract—Epoxy underfill is often required to enhance the reliability of flip-chip interconnects. This study evaluates the flow of typical epoxy underfill materials between parallel plates driven by capillary action. An exact model was developed to understand the functional relationship between flow distance, flow time, separation distance, surface tension, and viscosity for quasisteady laminar flow between parallel plates. The model was verified experimentally with a typical underfill material. The measured values of flow distance agreed well with the exact model. A new material parameter, the coefficient of planar penetrance, is introduced. This parameter measures the penetrating power of a liquid between parallel plates driven by capillary action. The effectiveness of gravity and vacuum as flow rate enhancements is explored.

I. INTRODUCTION

The use of flip-chip interconnects is attractive because of its high electrical performance, high interconnect density, and small size and weight [1]–[4]. Studies have shown that underfilling is required to ensure the reliability of the solder interconnect to organic substrates during thermal cycling [5]–[10]. In addition, underfill may be required for ceramic substrates if the die is large [11]–[15]. In both of these cases the time required for the underfill material to flow under the die can lead to partial curing of the underfill material before flow is complete. Excessive flow times can also lead to substantial manufacturing process delays. The objective of this study is to understand the flow of typical epoxy underfill materials under flip-chips.

II. UNDERFILL FLOW MODEL

The scanning electron micrograph in Fig. 1 shows a cured cross section of the progressing front of a typical filled epoxy underfill material under a mounted flip-chip. The flow of the underfill material under the die can be modeled as quasisteady, laminar flow between parallel plates driven by surface tension (capillary action), as shown schematically in Fig. 2.

This two-dimensional (2-D) model ignores the effects of the solder bumps, surface roughness, flux and other flow obstructions. The model also assumes an infinite supply of underfill material and ignores end effects.

Due to the very low flow rates, the Reynolds number for underfill flow is on the order of $10^{-5}$, well within the laminar region for parallel plate flow ($<10^5$). The Navier–Stokes equation for incompressible, quasisteady, laminar, Newtonian, 2-D horizontal flow [16] reduces to

$$\frac{\partial p}{\partial x} = -\mu \frac{\partial^2 V_x}{\partial y^2}$$

where $p$ is the pressure in the fluid at $x$, $\mu$ is the absolute viscosity of the fluid, $V_x$ is the velocity of the fluid, and the coordinates $x$ and $y$ are oriented as shown in Fig. 2. Since each side of (1) is independent of the other, the partial differential equation can be separated into two ordinary differential equations

$$\frac{d^2 V_x}{dy^2} = -\beta$$

where $\beta$ is a constant. Solving (2b) subject to the boundary conditions $V_x|_{y=h/2} = V_x|_{y=-h/2} = 0$ gives

$$V_x = \frac{\beta}{2\mu} \left( \frac{h^2}{4} - y^2 \right).$$

The speed of the front $(dL/dt)$ is equal to the average flow velocity $V_x$.

$$\frac{dL}{dt} = \frac{1}{h} \int_{-h/2}^{h/2} V_x dy.$$
Substituting (3) into (4), integrating and solving for $\beta$ gives

$$\beta = \frac{12 \mu}{h^2} \left( \frac{dL}{dx} \right).$$  \hspace{1cm} (5)$$

By substituting (5) into (2a), the head loss ($\partial p/\partial x$) can be expressed by the partial differential equation

$$\frac{\partial p}{\partial x} = -\frac{12 \mu}{h^2} \left( \frac{dL}{\partial t} \right).$$  \hspace{1cm} (6)

The Laplace–Young equation of capillarity states that the pressure drop across the free surface of a liquid-vapor interface, from the concave side to the convex side, is inversely proportional to the radius of curvature of the free surface [17], [18]. The radius of curvature of the free surface for the two dimensional case can be shown to be $h/2 \cos \theta$, where $\theta$ is the wetting angle that the underfill makes with the planes (see Fig. 2). From the Laplace–Young equation, the pressure drop across the free surface ($\Delta p$) can be expressed as

$$\Delta p = \frac{2 \gamma \cos \theta}{h}.$$  \hspace{1cm} (7)

where $\gamma$ is the surface tension of the liquid-vapor interface. Since $dL/dt$ is independent of $x$ and $d\gamma/dx$ is independent of $t$, (6) can be separated into two ordinary differential equations

$$\frac{dp}{dx} = \Gamma$$  \hspace{1cm} (8a)

and

$$-\frac{12 \mu}{h^2} \left( \frac{dL}{\partial t} \right) = \Gamma$$  \hspace{1cm} (8b)

where $\Gamma$ is a constant. Since the boundary condition at $x = L$ is on the convex side of the interface $p|_{x=L} = -\Delta p$. Solving (8a) subject to the boundary conditions

$$p|_{x=0} = 0, \quad p|_{x=L} = -\frac{2 \gamma \cos \theta}{h}$$

gives

$$\Gamma = -\frac{2 \gamma \cos \theta}{hL}.$$  \hspace{1cm} (9)

Substituting (9) into (8b) and solving subject to the conditions

$$L|_{t=0} = 0, \quad L|_{t=t_f} = L_f$$

where $t_f$ is the flow time and $L_f$ is the flow distance gives

$$\frac{12 \mu}{h^2} \frac{L_f^3}{2} = \frac{2 \gamma \cos \theta}{h} \cdot t_f.$$  \hspace{1cm} (10)

Rearranging (10) and dropping subscripts gives

$$L = \sqrt{\frac{ht \gamma \cos \theta}{3 \mu}}.$$  \hspace{1cm} (11)

Alternatively, solving (11) for the flow time gives

$$t = \frac{3 \mu L^2}{h \gamma \cos \theta}.$$  \hspace{1cm} (12)

The flow time for viscous flow between parallel plates driven by capillary action is inversely proportional to the surface tension, separation distance, and the cosine of the wetting angle, and directly proportional to the viscosity and the square of the flow distance.

The quantity $(\gamma \cos \theta)/2 \mu$ measures the penetrating power of a liquid into a horizontal capillary tube, and was defined by Washburn [19] as the coefficient of penetrance. Since underfill flow under flip-chips more closely resembles flow between parallel plates, we can define an analogous term as the coefficient of planar penetrance ($\Phi$), as

$$\Phi \equiv \frac{(\gamma \cos \theta)}{3 \mu}.$$  \hspace{1cm} (13)

This parameter measures the penetrating power of a liquid into a gap between parallel plates, and has units of velocity. Substituting the coefficient of planar penetrance into (11) and (12) gives

$$L = \sqrt{\Phi \frac{h t}{\gamma \cos \theta}}.$$  \hspace{1cm} (14)

and

$$t = L^2/\Phi h.$$  \hspace{1cm} (15)

In practice, most underfill materials wet the parallel plate surfaces, resulting in near zero wetting angles as can be seen in Fig. 1. In this case, $\cos \theta \approx 1$, leaving $\Phi/3 \mu$. Assuming ideal wetting, the penetrating power of a liquid into a gap between parallel plates is characterized by $1/3$ of the ratio of the surface tension of the liquid to its viscosity. Since this parameter may be strongly related to the temperature of the underfill material, it should be measured and specified at the recommended flow temperature, which is often higher than room temperature.

III. EMPIRICAL VERIFICATION OF THE MODEL

The exact relationship developed in (14) was verified experimentally. The surface tension and viscosity of a typical filled epoxy underfill material were measured and used to calculate the coefficient of planar penetrance ($\Phi$). This value was then substituted into (14) to calculate the flow distance ($L$). The actual flow distance of the underfill material was determined by flowing the underfill between parallel plates. The model was verified by comparing the flow distance predicted by (14) to the actual flow distance from the parallel plate flow test.

The viscosity of the underfill material was characterized with a temperature controlled rheometer. A 4.0 cm parallel plate with a gap of 175 $\mu$m was used. The viscosity was a very strong function of temperature. The viscosity was nearly constant over a shear stress range of 20 to 100 Pa, indicating highly Newtonian behavior. A viscosity of 0.775 kg/ms was measured at a temperature of 80°C, and a shear stress of 100 Pa.

The surface tension of the underfill material was determined experimentally by measuring the capillary rise in 0.50 mm diameter glass capillary tubes at 80°C. Using a receding meniscus, a value of 0.036 N/m was measured. Using a progressing meniscus, a value of 0.015 N/m was measured. Since underfill flow involves a progressing meniscus, the value of 0.015 N/m from the progressing meniscus was substituted for the $\gamma \cos \theta$ term in the calculation of the coefficient of planar penetrance. The use of this value assumes that the surface of the capillary tube is similar as the surfaces of the parallel plates.
The coefficient of planar penetrance of the underfill at 80°C was calculated from the measured values of viscosity and surface tension to be \( \Phi \cong \frac{(\gamma \cos \theta)}{3\mu} \approx 0.0064 \text{ m/s}. \)

The actual flow distance was determined with a simple parallel plate flow experiment. The experimental setup is shown in Fig. 3. A 125-\( \mu \text{m} \) thick piece of shim stock was placed under one edge of a glass-ceramic sandwich. The slight inclination of the glass with respect to the ceramic resulted in a continuously varied separation distance from zero to 125 \( \mu \text{m} \). The glass-ceramic sandwich was placed on a temperature controlled heating plate to maintain the temperature of the underfill at 80°C during the flow. At \( t = 0 \), the underfill was dispensed into a reservoir along one of the inclined edges. The flow pattern was then videotaped through the glass plate, along with a stop-watch which recorded the flow time.

The solid white lines in Fig. 4 are calculated from (14), evaluated at \( \Phi = 0.0064 \text{ m/s} \). The black areas of the plots are the actual extent of the underfill flow as a function of separation distance and flow time as captured from the videotaped flow experiment. The trend as well as the absolute values of the actual underfill flow agree remarkably well with the model at separation distance of approximately 60 \( \mu \text{m} \) or greater. The discrepancy of the actual flow distance at a separation distance below 60 \( \mu \text{m} \) is likely due to the fact that the spherical filler particles, which were up to 35 \( \mu \text{m} \) in diameter, could not flow freely through these small gaps.

The rough profile of the underfill fronts is likely a result of the fingering effect described by German [20]. Fingering can be caused by localized variations in the filler packing density. Finally, due to the extent of the flow at \( t = 1800 \text{ s} \), some of the underfill may have displaced laterally (from right to left) causing some distortion in the actual flow data.

Both the model and the data also show that the flow rate decreases as the front progresses. Qualitatively, this can be explained by the fact that the capillary force driving the flow remains constant, while the amount of material being pulled along, dissipating energy through viscous shearing, increases.

IV. EFFECTS OF GRAVITY AND VACUUM ON FLOW RATE

With this basic understanding of the parameters affecting underfill flow and the measured physical properties of a typical epoxy underfill material, the effectiveness of gravity (inclined or vertical flow) and vacuum as flow rate enhancements can be readily estimated to first order. This can be done by comparing the magnitude of the pressure generated by the enhancement to the capillary pressure generated at the liquid-vapor interface of the unenhanced flow.
Consider the case where the flip-chip is oriented vertically such that the underfill flows from top to bottom aided by the hydrostatic pressure induced by gravity acting on the underfill. Assuming underfill with a \( \gamma \cos \theta \) value of 0.015 N/m was used on a chip with a 75 \( \mu \)m standoff (separation distance), the capillary pressure given by (7) would be 395 Pa. The median hydrostatic pressure generated during the flow would be \( \rho g H/2 \) where \( \rho \) is the mass density of the underfill, \( g = 9.81 \text{ m/s}^2 \), and \( H \) is the chip size. A typical underfill mass density of 1600 kg/m\(^3\) on a 10 mm square flip-chip would generate a median hydrostatic pressure of 78 Pa. Since the hydrostatic pressure is only about 1/5 of the capillary pressure, it is unlikely to significantly enhance the flow rate, especially when the gap (separation distance) is small. Vacuum enhancements can generate driving pressures of up to one atmosphere (10\(^5\) Pa). Since this is more than 250 times the capillary pressure, the vacuum enhancement will have a significant effect on the flow rate. An example of the use of vacuum to enhance underfill flow has been demonstrated by Banerji et al. [21].

V. CONCLUSION

- An exact model was developed for understanding the flow time \( t \) for quasisteady, laminar flow between parallel plates driven by capillary action, as a function of flow distance \( L \), separation distance \( h \), wetting angle \( \theta \), surface tension \( \gamma \), and the absolute viscosity \( \mu \). The flow time is given by

\[
t = \frac{3\mu L^2}{h\gamma \cos \theta},
\]

The flow time for viscous flow between parallel plates driven by capillary action is inversely proportional to the surface tension, separation distance and cosine of the wetting angle, and directly proportional to the viscosity and the square of the flow distance. This model agreed well with experimental results of a typical underfill material flowing between plates of glass and ceramic.

- The flow rate of an underfill is strongly related to two underfill material properties: surface tension \( \gamma \) and viscosity \( \mu \). The quantity

\[
(\gamma \cos \theta)/3\mu
\]

was defined as the coefficient of planar penetration \( \Phi \) where \( \theta \) is the wetting angle of the underfill to the planes. The \( \gamma \cos \theta \) term can be determined by measuring the capillary rise of a progressing meniscus. This parameter measures the penetrating power of a liquid into a gap between parallel plates, and has units of velocity. This parameter was strongly related to the temperature of the underfill material.

- Gravity will not significantly enhance the flow rate of underfill materials flowing under flip-chips. Vacuum enhancement, however, can generate pressures of more than 250 times the capillary pressure, and will effectively enhance underfill flow rates.

VI. RECOMMENDATIONS

- In order to characterize the flow behavior of an underfill material under a flip-chip, the coefficient of planar penetration should be specified at the recommended flow temperature.

- Gravity (inclined or vertical flow) should not be pursued as a method to enhance underfill flow rates. Vacuum enhancements, however, should be pursued.

- This work does not consider the effects of surface roughness, solder bumps, flux residues, or other obstructions on the underfill flow. This model also does not consider non-Newtonian flow behavior. A more complicated model could be developed to include these factors, however its usefulness would be limited due to additional complexity. An empirical approach, based on the simple model shown here, is recommended for optimizing processes including these other factors.

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REFERENCES


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