

Underflow Process for Direct-Chip-Attachment Packaging

Gary L. Lehmann, T. Driscoll, N. R. Guydosh, P. C. Li, and Eric J. Cotts

Abstract—In flip-chip packaging, an underfill mixture is placed into the chip-to-substrate standoff created by the array of solder bumps, using a capillary flow process. The underfill mixture is densely filled with solid silica particles to achieve the desired effective coefficient of thermal expansion. Thus, during the flow process the underfill mixture is a dense suspension of solid particles in a liquid carrier. The flow behavior is a complex function of the mixture properties, the wetting properties, and the flow geometries. This paper reports on the use of a plane channel capillary flow to characterize underfill materials. We define and explore a metric termed the flow parameter which scales as $\sigma \cos(\theta)/\mu_{app}$. The measured flow behavior provides evidence that both the contact angle (θ) and the suspension viscosity (μ_{app}) vary with time under the influence of changing flow conditions. The flow parameter is useful in detecting both of these phenomena. The contact angle variation is consistent with the literature on wetting dynamics, where θ is observed to be a function of the contact line speed. Nonlinear fluid behavior is evident for both model suspensions and commercial underfill materials.

Index Terms—Capillary flow, DCA, non-Newtonian, underfill.

I. INTRODUCTION

IN direct-chip-attachment (DCA) a chip is mounted directly to a substrate (card) using a grid-array of solder bumps. For protection of both the chip and the solder joints an epoxy resin underfills the standoff region between the chip and substrate. A capillary flow process is used to draw the underfill into this region (Fig. 1). To achieve reliable fatigue life of the solder joint, the coefficient of thermal expansion of the cured underfill must approach that of the solder. A mixture with the desired effective coefficient of thermal expansion is commonly obtained by adding a high volume fraction of solid particles to an epoxy. The effects of such fillers on the mechanisms of the capillary flow process are not well understood. Therefore, we are conducting an investigation of the flow process that is used to place underfill materials in DCA packaging. We seek to identify the means of achieving higher underflow speeds, and to develop the proper metrics for characterizing these flow processes. Experiments are performed to assess the effects

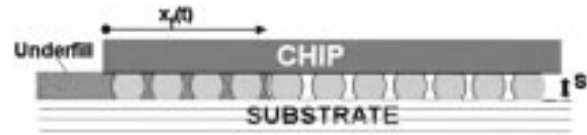


Fig. 1. Simplified diagram of an underfill flowing between a chip and a substrate. The standoff s between chip and substrate is shown. The solder balls joining the chip and substrate are sketched in the figure. In this example, the underfill flows from one side and the distance flowed is indicated with the arrow from $x = 0$ to the front position $x_f(t)$.

on underfill flow of variations in parameters describing the particles, the liquid carrier, and aspects of the flow geometry.

The essential features of a capillary flow of a Newtonian liquid between parallel plates are well described by the simple formula

$$x_f^2 = \frac{\sigma \cos(\theta_w) s t}{3\mu}. \quad (1)$$

Here, x_f is the position of the liquid-air front at time t , σ is the surface tension, θ_w is the wetting angle, s is the plate spacing, and μ is the Newtonian liquid viscosity. Termed the Washburn model, it is cited in recent efforts to characterize the flow of underfill encapsulants [1]–[4]. While this model is inadequate for the more sophisticated problem of the flow of a dense suspension through an obstruction field, between parallel plates it does provide a starting point for an understanding of our complicated flow problem. An illustration of these points can be seen by considering a previous comparison by Gamota *et al.* between the times for a variety of different commercial underfill mixtures to underfill a 0.66-cm long chip, and the times predicted on the basis of (1) for these flows (Fig. 2). Measurements of μ and σ were performed and θ_w was estimated to be zero degrees for all flows. Then, using (1), times to flow the length of the chip $x_c = 0.66$ cm with a standoff $s = 125 \mu\text{m}$ were predicted

$$t = \frac{x_c^2 3\mu}{\sigma \cos(\theta_w) s}. \quad (2)$$

Fig. 2 compares the measured and predicted times from Gamota *et al.* Given the complexity of the flow process the Washburn model provides a reasonable first-order approximation. However the flow times are measurably faster than those predicted and clearly the Washburn model has deficiencies. In this paper, we identify significant flow features that the Washburn model does not consider.

¹The subscript w is used to emphasize that the Washburn model analysis assumes a constant value for the contact angle.

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G. L. Lehmann, T. Driscoll, P. C. Li, and E. J. Cotts are with the Physics Department, The State University of New York, Binghamton, NY 13902 USA. N. R. Guydosh is with Harvard University, Cambridge, MA 02138 USA. Publisher Item Identifier S 1070-9886(98)05296-2.

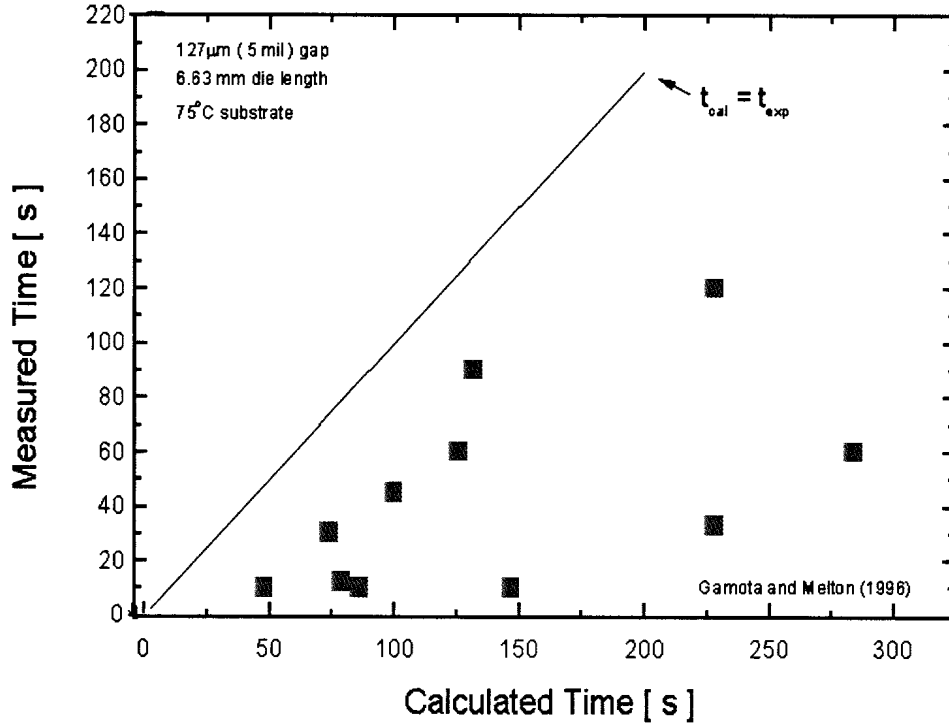


Fig. 2. Comparison of measured times t_{exp} to flow selected commercial encapsulants 0.66 cm under a quartz die of standoff 125 μm to calculated times t_{calc} .

The thrust of this paper is to report the use of plane channel capillary flow to characterize underfill mixtures. We define and explore a metric, termed the flow parameter, which is related to the rate of flow of the underfill. We use this metric to illustrate that both the apparent shear viscosity and the contact angle are dynamic quantities. They both vary with time under the influence of changing flow conditions.

II. THE CAPILLARY FLOW CELL

Key features of the underfill flow process can be represented by the capillary flow of a liquid-solid mixture into a plane channel. In our initial consideration of this problem, the channel is free of obstructions (i.e., the solder bumps are absent). The position of the mixture-air interface (x_f) is measured as a function of time (t)

$$x_f = F(t; s, T, \text{suspension}) \quad (3)$$

for a given channel spacing (s), temperature (T) and suspension materials.

It is useful to introduce a quantity we term the flow parameter, defined by

$$b(t) \equiv \frac{d}{dt} x_f^2 \quad (4)$$

for use as a metric to describe these capillary flows. While the Washburn model predicts a constant value

$$b_w = \frac{\sigma \cos(\theta_w)}{3\mu} \quad (5)$$

we observe that b is a function of time. This time dependence is indicative of variations in both the contact angle θ and the apparent viscosity with flow conditions.

The Washburn model is based on the assumptions of a quasi-steady (Reynolds number <1), fully developed (Poisuille) channel flow, and that the liquid-air interface is a circular arc (i.e., nearly the equilibrium shape). We review this formulation to obtain an improved interpretation of the flow parameter. The model is extended to allow for non-Newtonian behavior, in which the viscosity is a function of the strain-rate ($\dot{\gamma}$). Under the application of a pressure-gradient ($\Delta p/x$) the mean speed of a fully developed channel flow may be written as

$$u_m = \frac{s^2}{12\mu_{\text{app}}} \times \left(\frac{\Delta p}{x} \right) \quad (6)$$

where x is the coordinates parallel to the flow direction. To allow for non-Newtonian behavior an apparent viscosity, μ_{app} , is introduced in place of the Newtonian value of μ . Departure from Newtonian behavior is manifest by the variation of μ_{app} with the apparent strain-rate, γ_{app} , i.e.,

$$\mu_{\text{app}} = f_a \left(\gamma_{\text{app}} = \frac{4\dot{\mu}_m}{s} \right). \quad (7)$$

A detailed discussion of nonlinear fluids and the use of an apparent viscosity is available in Macosko [5]. Now considering the motion under capillary action, the pressure jump associated with the curvature of the advancing front is modeled as

$$\Delta p = 2\sigma \cos \frac{(\theta)}{s}. \quad (8)$$

If the channel entrance and exit are at equal pressures (and pressure losses in the upstream air are negligible), then Δp of (8) is taken to be that driving the flow. Combining (6) and (8)

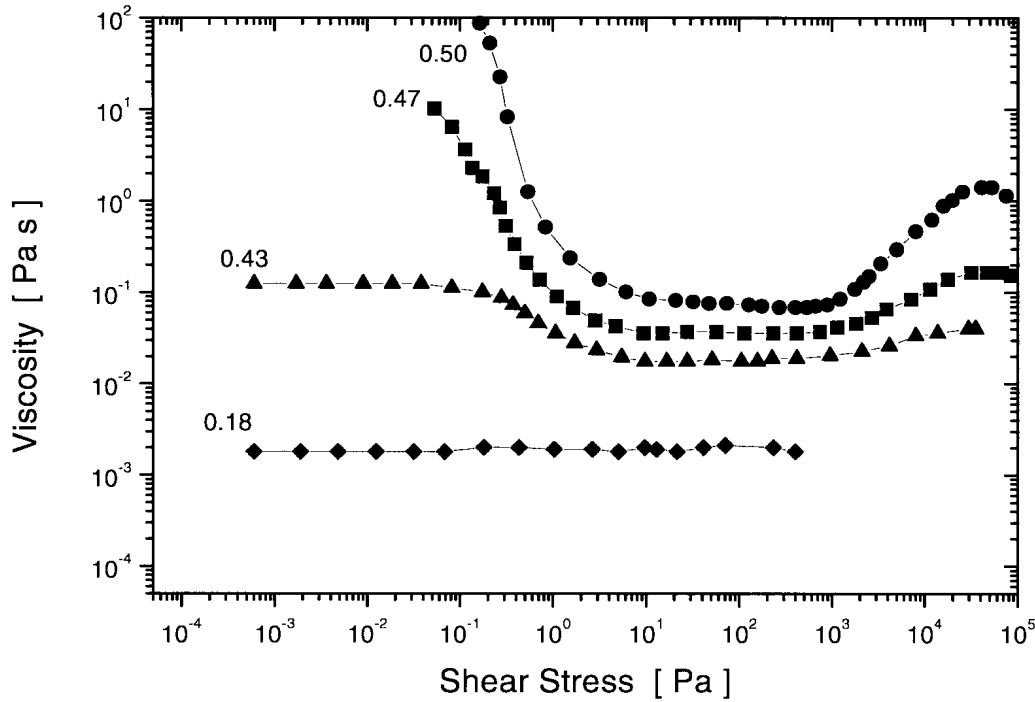


Fig. 3. Curves for the apparent viscosity versus shear stress for suspensions of different volume fractions. The volume fractions are noted in the figure. The data are from the work of Laun *et al.* [6].

and writing u_m as dx_f/dt one obtains

$$\frac{d}{dt}x_f^2 = \frac{\sigma \cos(\theta)}{3\mu_{app}}s. \quad (9)$$

Here we have recovered the flow parameter, $b(t)$. Equation (9) may be used to evaluate the apparent shear-rate as

$$\gamma_{app} = \frac{2\sigma \cos(\theta)}{3\mu_{app}} \frac{1}{x_f}. \quad (10)$$

In the channel entrance (small x_f) there is a strong contribution to γ_{app} variation by the $1/x_f$ term. Thus any nonlinear behavior is emphasized by the rapid γ_{app} variation.

Finally to obtain a closed form solution let us consider a power law fluid, and approximate θ with the constant valued θ_w . Here the viscosity is modeled as

$$\mu = \kappa(\gamma)^{1-m/m} \quad (11)$$

where κ and m are constants. A similar development to that providing (9) leads to

$$\begin{aligned} \frac{dx_f}{dt} &= A \left(\frac{2\sigma \cos(\theta_w)}{sx_f} \right)^m \text{ with} \\ A &= \left(\frac{1}{2+m} \right) \frac{(s/2)^{m+1}}{\kappa^m}. \end{aligned} \quad (12)$$

Integration of (12) is performed subject to the condition that $x_f = 0$ at $t = 0$. Upon rearrangement one obtains

$$x_f^2 - \left[(1+m)A \left(\frac{2\sigma \cos \theta_w}{s} \right)^m \right]^{(2/1+m)} t^{\frac{2}{1+m}}. \quad (13)$$

Differentiation with respect to time yields an expression for the flow parameter corresponding to a power law fluid and a

constant wetting angle

$$\begin{aligned} b(t) &= \frac{2}{1+m} \\ &\cdot \left\{ (1+m)A \left(\frac{2\sigma \cos(\theta_w)}{s} \right)^m \right\}^{(2/1+m)} t^{(1-m/1+m)}. \end{aligned} \quad (14)$$

Note in (13) and (14) that for a linear fluid ($m = 1$), one recovers the Washburn model. For shear thinning ($m > 1$) and thickening ($m < 1$) the flow parameter decreases or increases with increasing time, respectively. This is a signature effect of nonlinear viscosity behavior that can be observed using the flow parameter as a metric for the capillary flow cell.

A. Modeling Dense Suspensions

The application of the models introduced requires that one adopt a single phase, “mixture-fluid” model to replace the actual two-phase suspension of particles. Some explanation for the discrepancies between the predicted and observed times, as epitomized in Fig. 2, can be attributed to the use of a single value for the underfill mixture viscosity. Our studies indicate that a simple Newtonian viscosity model is not adequate to capture the flow behavior of underfills. A dependence of the mixture viscosity on strain-rate must be accounted for. This behavior is epitomized by the data of Laun [6], as shown in Fig. 3. Here mixture viscosity is plotted versus strain-rate for four different model suspensions, each of different volume fraction, ϕ . Variations of viscosity with strain-rate (or shear stress) are illustrated in Fig. 3, most dramatically by the curve for the $\phi = 0.5$ suspension. Commercial underfill mixtures generally have particle volume fractions close to $\phi = 0.5$, and

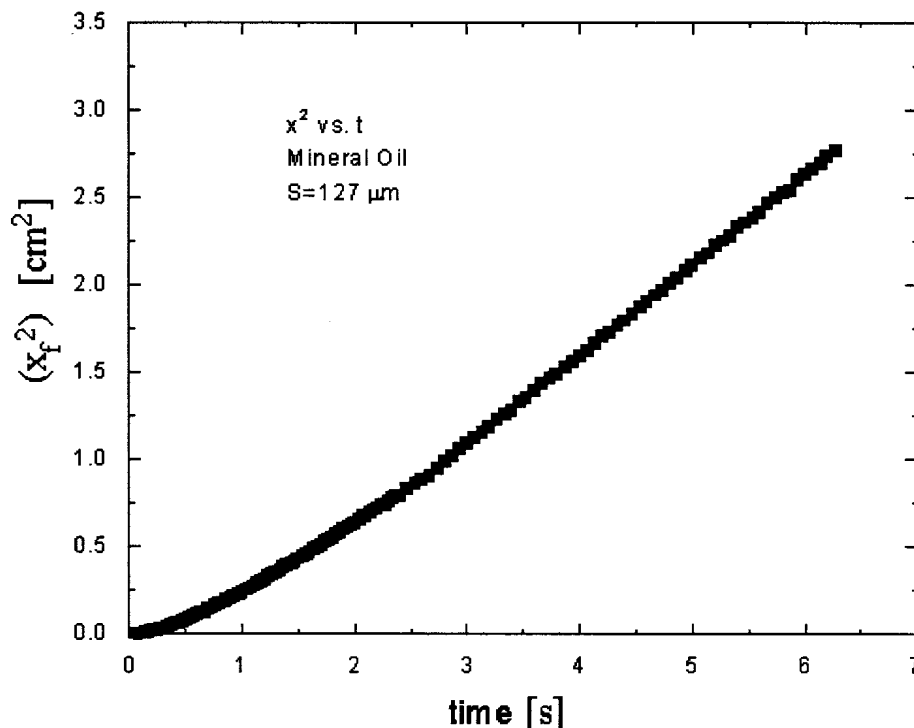


Fig. 4. A plot of the front position squares as a function of time for the capillary flow of mineral oil; $s = 127 \mu\text{m}$ and 23°C .

we have observed both shear thinning and shear thickening in commercial underfill mixtures. Predictions of flow times must not only account for variations of underfill mixture viscosity with shear-rate (Fig. 3), but may also depend on the ratio of particle size to plate spacing.

III. EXPERIMENTAL RESULTS

The flow cell channel walls consist of smooth, well-cleaned glass plates for all results reported in this paper. Precision spacers are used to maintain an accurate, parallel plate spacing. The spacers act as side walls such that the flow channel has a low aspect ratio (generally less than 0.01) rectangular cross-section. The axial length of the channel is 8 cm. The flow channel rests on a large aluminum mass, instrumented with thermocouples. Sensitivity of the flow behavior to temperature has been noted and care is taken to maintain a known, uniform temperature of the flowing material. In this paper data for a vertical orientation (capillary rise) is only reported in the measurement of the equilibrium wetting strength parameter $[\sigma \cos(\theta)]$. All reported flow studies have been conducted in a horizontal orientation.

We have conducted an experimental investigation for a number of dense suspensions, including both commercial underfill mixtures as well as model suspensions. A selected set of these experiments, which illustrate the key concepts of this paper, is reported. The first data set presented is on the flow of mineral oil. This is a well characterized Newtonian liquid. It provides a vehicle to explore the dynamic nature of the contact angle. The second data set is a model suspension in which neutrally buoyant solid spheres are used to eliminate the issue of settling. By contrast particles in commercial underfill mixtures are negatively buoyant and settling can play a role.

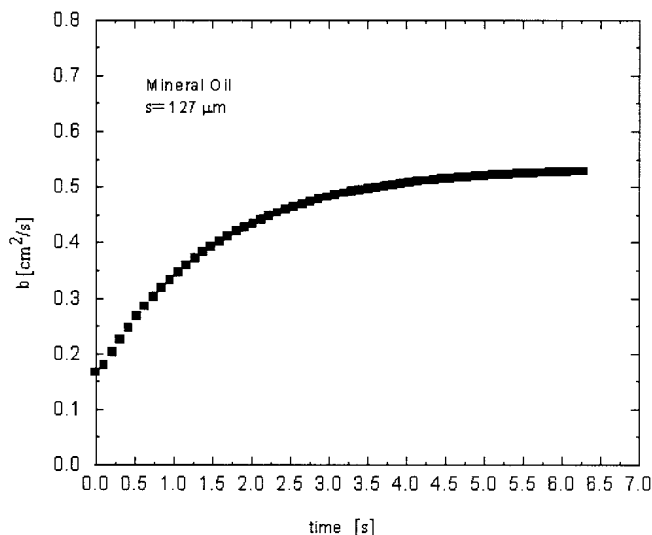


Fig. 5. The flow parameter variation with time for the capillary flow data set shown in Fig. 4.

Finally we present measurements taken for three commercial underfill mixtures.

A. Standard Newtonian Fluid—Mineral Oil

Capillary flow of mineral oil was examined for a series of plate spacings ($38\text{--}500 \mu\text{m}$) at a temperature of 23°C . The results are epitomized by those displayed in Fig. 4, which plots the variation of x_f^2 with time at a value of $s = 127 \mu\text{m}$. Deviation from the simple model of (1) is seen at early times, as elucidated in Fig. 5, a plot of b versus t . It is immediately clear that a single value of b is inadequate at early times, even for a Newtonian fluid. The data are well represented by the

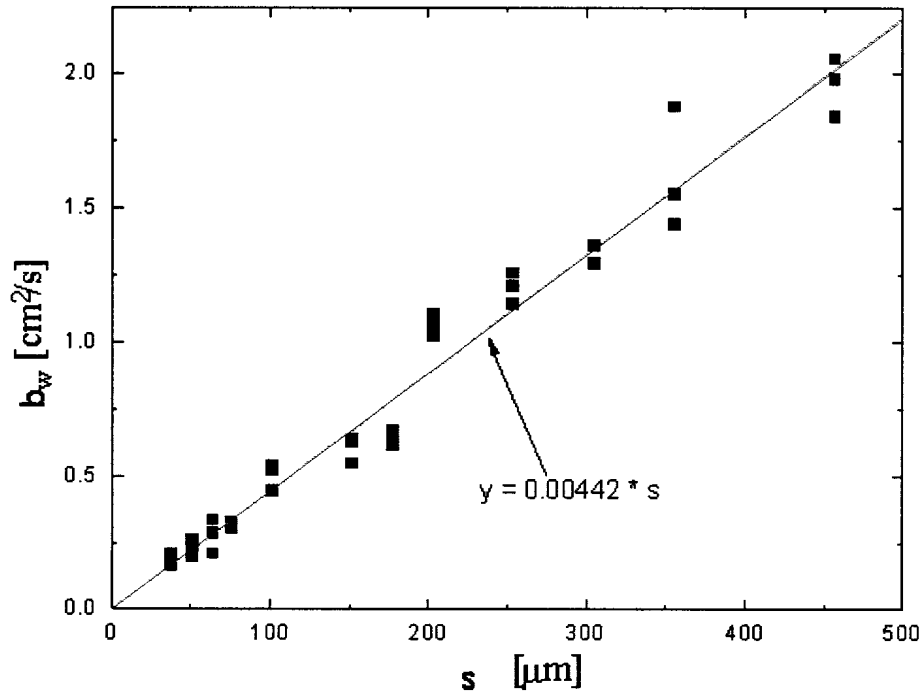


Fig. 6. A plot of the large time flow parameter b_w as a function of channel spacing s for the capillary flow between parallel glass plates of mineral oil at a temperature of 23 °C. The flow parameter is defined as the constant value of the time derivative of the front position squared observed at long times; ■ the flow parameter, b_w . Also shown in the figure with a straight line is a linear fit to the data.

functional form

$$x_f^2(t) = b_w t + a_2 \left(\exp \left(\frac{-t}{a_3} \right) - 1 \right)$$

which has the associated flow parameter

$$b = b_w - \frac{a_2}{a_3} \exp \left(\frac{-t}{a_3} \right). \quad (15)$$

This function becomes identical to the Washburn model at large time ($t \gg a_3$). At small time deviation from the Washburn model is characterized by a nonzero, positive value of a_2 . Let us assume that the proper scaling of the flow parameter is $b \sim \sigma \cos(\theta) s / \mu$ [cf., (5)]. For a Newtonian liquid σ , s and μ are all constants. Thus, the contact angle, θ , must vary with time to account for the early time variation in $b(t)$. This is consistent with the literature on dynamic wetting where it is generally accepted that the contact angle varies with the speed of the contact line (u_{cl}) [7]–[9]. A typical empirical correlation, often termed the mobility relation, is $\theta = f(u_{cl}(t); \theta_a)$, where $f(u_{cl})$ is a monotonically increasing function and θ_a is the static angle of advance. A model that incorporates the mobility relation would predict that in the initial stage of this flow process $\theta > \theta_a$, but that θ decreases rapidly, with $\theta(t) \rightarrow \theta_a$ in the large time regime. Thus as time increases one recovers the Washburn model behavior as $\cos(\theta)$ becomes essentially constant.

Let us now focus on the later time behavior where we observe b to be essentially a constant (close to b_w) with respect to time. We examine this behavior and compare it with (5) by means of a plot of the measured values of b_w versus s for values of s ranging from 38–500 μm . This plot is displayed in Fig. 6, where a linear fit to the data of Fig. 6 is found to be

0.442 m/s. According to (5) this slope should be given by

$$\frac{db_w}{ds} = \frac{\sigma \cos \theta_w}{3\mu}. \quad (16)$$

For a Newtonian liquid one should be able to make independent measurements of the viscosity and the capillary driving force and predict the value of db_w/ds using (16). Such measurements have been performed, as are briefly outlined here. The capillary parameter, $\sigma \cos(\theta_e)$, is the product of the surface tension and the equilibrium contact angle, θ_e . It was measured by determining the equilibrium height (H) of a column of liquid contained by two vertically oriented plates of spacing s . The column either rises from or recedes into a reservoir. Both the reservoir and the liquid front are exposed to the same ambient pressure. Thus in a static balance the capillary forces match the weight of the liquid column. Under these conditions one can show that

$$H = \frac{2\sigma \cos \theta_e}{\rho g} \frac{1}{s}. \quad (17)$$

The results of these measurements are displayed in Fig. 7, in a plot of H under conditions of both capillary fall and rise versus the inverse plate spacing. According to (17), the slope of a linear fit to this data is given by

$$\frac{dH}{d\left(\frac{1}{s}\right)} = \frac{2\sigma \cos \theta_e}{\rho g} \quad (18)$$

where ρ is the density of the mineral oil, measured as $\rho = 0.834 \text{ g/cm}^3$, and g is the gravitational constant. A linear fit to our data yields a value of $dH/d(1/s) = 7.20(10^{-6}) \mu^2$.

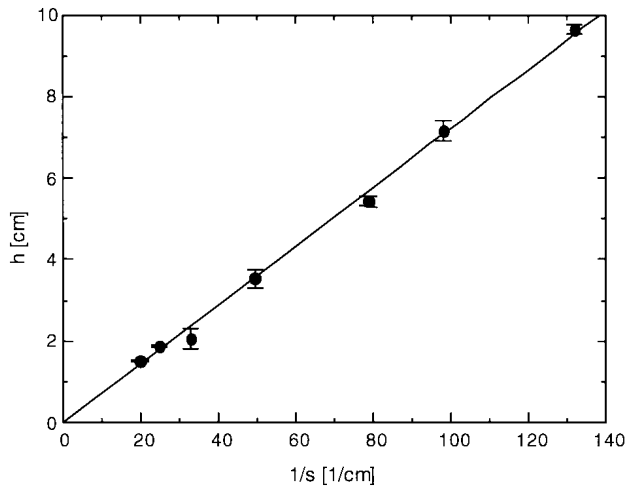


Fig. 7. A plot of H under conditions of both capillary fall and rise versus the inverse plate spacing.

Interpreted in terms of (18) this yields a value of $\sigma \cos(\theta_e) = 2.94(10^{-2})$ N/m.

Measurement of shear viscosity was conducted using a CSL² 500 Rheometer manufactured by TA Instruments. The measurement geometry was a rotating parallel disk configuration, with a 2 cm disk radius. For mineral oil the measured viscosity was independent of strain rate. At a temperature of 20 °C the measured value was $\mu = 0.0184$ Pa·s. Combining our measurements of μ and $\sigma \cos(\theta_e)$ we arrive at a predicted value of db/ds for mineral oil, independent of the capillary flow cell results. We find that $\sigma \cos(\theta_e)/3\mu = 0.51$ m/s. This value of db/ds determined from rheology and capillary rise data, ($db/ds = 0.51$ m/s) is slightly larger than the value determined from parallel plate capillary flow measurements, $db/ds = 0.44$ m/s.

B. Model Suspension—Neutrally Buoyant Spheres

The flows of mixtures consisting of polystyrene spheres in propylene glycol are reported next. The solid spheres had a narrow size distribution with a mean diameter of $5.5 \mu\text{m}$ and density of 1.05 g/cm^3 . The propylene glycol has a viscosity of $0.045 \text{ Pa} \cdot \text{s}$ over a range of $5 \text{ s}^{-1} < \dot{\gamma} < 1000 \text{ s}^{-1}$ and a density of 1.04 gm/cm^3 . Experiments have been conducted for solid volume fractions of $\phi = 0.10, 0.20, 0.28, 0.40, 0.46$, and 0.50 over a range of channel spacings from $38\text{--}254 \mu\text{m}$. For the majority of the experiments ($\phi \leq 0.40$), the flow distance squared (x_f^2) was essentially linear with respect to time, corresponding to a Newtonian fluid behavior. However, at $\phi = 0.50$ we find evidence of nonlinear fluid behavior. Fig. 8 plots the variation of position squared with time at $\phi = 0.50$ and $s = 76 \mu\text{m}$. The measured data (solid symbols) have a distinct curvature. For comparison a model power law, based on $x_f^2 = 6.06(10^{-4})t^{(2/(1+m))}$ with $m = 0.55$, is also plotted. Recall from the previous discussion that $m < 1$ corresponds to a shear thickening fluid. The corresponding flow parameters obtained from the data and the model power law curve are plotted on Fig. 9. The flow parameter varies by a factor of over two. The trend of increasing $b(t)$ is indicative of the shear thickening behavior of this dense suspension. It is clear

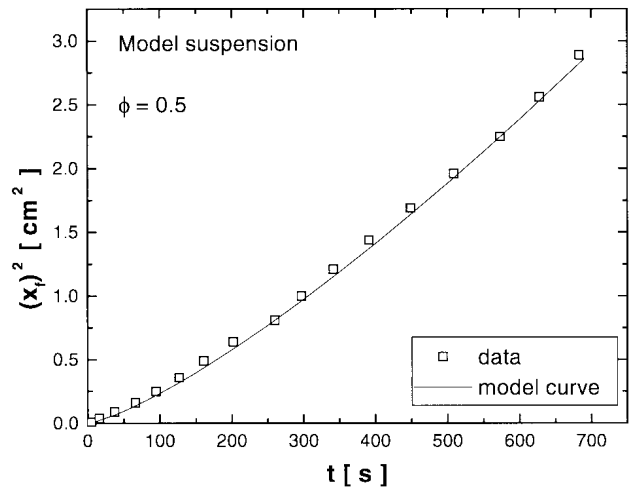


Fig. 8. A plot of the square of the front position as a function of time for the capillary flow between parallel glass plates of a suspension of polystyrene spheres in propylene glycol. The volume fraction of the glass spheres was 0.50 . The channel spacing was $76 \mu\text{m}$; $\square$ the measured data; the straight line is a model curve.

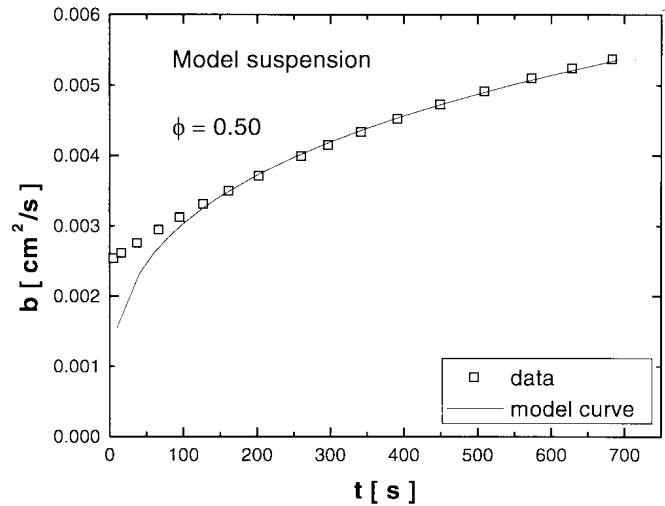


Fig. 9. A plot of the time derivative of the data of Fig. 8 as a function of time; $\square$ the time derivative of the data of Fig. 8. The straight line is a model curve.

that a single value of b fails to capture the complex behavior of the viscosity of dense suspensions.

C. Commercial Underfills

Flow experiments are being conducted with a number of commercial underfills. Representative results are shown for three underfill mixtures which are denoted as A, B, and C. The separations utilized in these experiments covered a range from $38\text{--}254 \mu\text{m}$. The underfills were in a room temperature environment for one hour before the flow experiments. The flow apparatus was heated to a nominal temperature of $70 \text{ }^\circ\text{C}$. Thermocouples also were placed at the entry point for the underfill to ensure that temperature distribution was in range.

Fig. 10 presents the variation of position squared with time for the vendor supplied underfill mixtures A, B, and C, respectively, at a spacing of $s = 102 \mu\text{m}$. Examination reveals distinct differences in behavior of these three underfills.

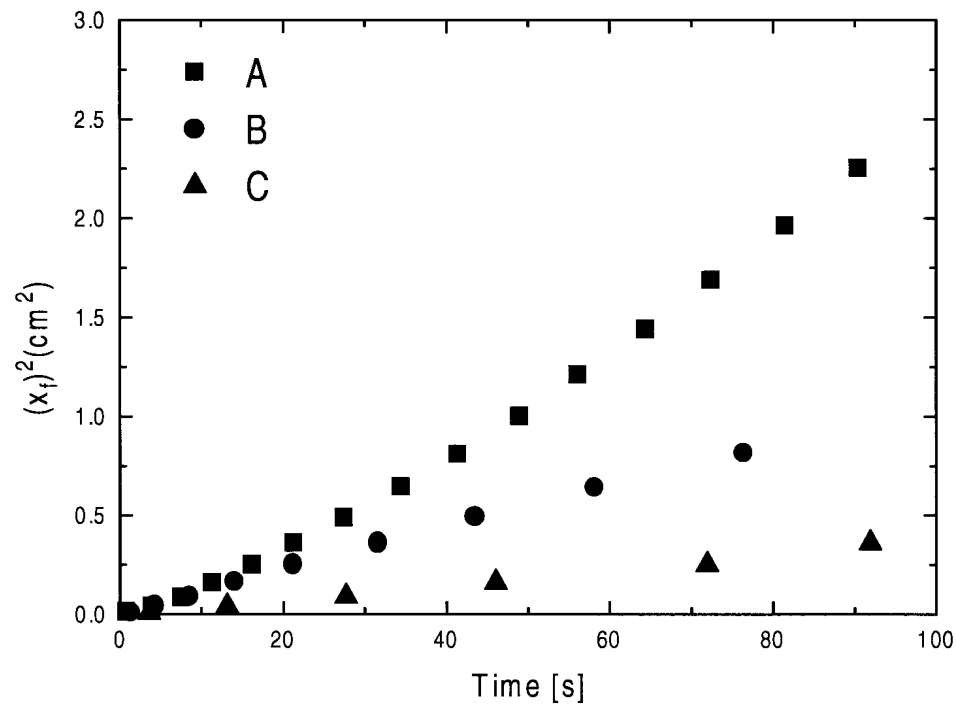


Fig. 10. The variation of position squared with time for the vendor supplied underfill mixtures A, B, and C, respectively at a spacing of $s = 102 \mu\text{m}$. A is ■, B is ●, and C is ▲.

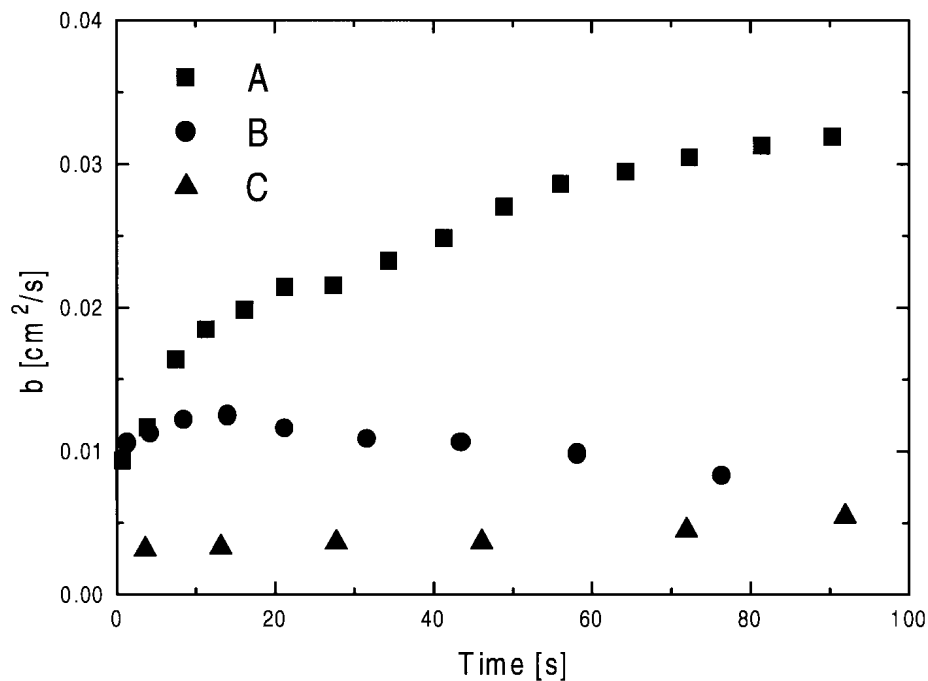


Fig. 11. A plot of the time derivative of the data of Fig. 10 as a function of time. A is ■, B is ●, and C is ▲.

Mixture A flowed faster, farther, and with greater regularity than underfill B or C. Furthermore, with underfill mixtures B and C flow ceased after a number of centimeters, while A was able to underfill the entire flow channel (8 cm). Fig. 11 shows the flow parameter variation with time for the three data sets in Fig. 10. The best flowing underfill, A, correspondingly has the larger value of the flow parameter. The initial values of A and B are nearly the same but they rapidly diverge. For B the time profile is nearly flat but for A the flow parameter

is increasing with time. An increase in b is indicative of a shear thickening viscosity, which corresponds to a decrease in apparent viscosity with increasing time. At larger spacings the flow parameters of underfill mixtures B and C were clearly observed to decrease with time. A mixture exhibiting a decreasing $b(t)$ profile will have a rapid decrease in flow speed and relatively shorter maximum flow distance, when compared to a flat or increasing $b(t)$ profile. This behavior can indicate a shear thinning viscosity, as well as particle settling.

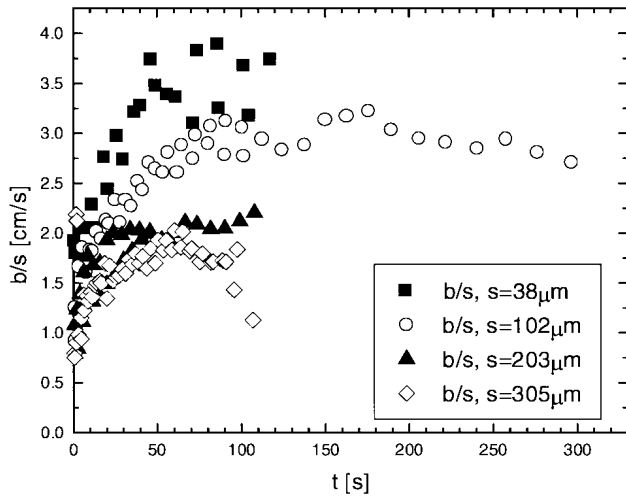


Fig. 12. Plots of the time derivative of the square of the front position divided by the plate spacing as a function of time for commercial underfill A. The underfill underwent flow between parallel glass plates of different spacings, s . All of the flows were at a temperature of 70 °C.

In any case, it is clear that a single value of b is an inadequate description of the flow behavior.

The Washburn model shows that b/s is a constant value, independent of s , for a given liquid and channel surface. Our linear fluid data are in agreement with this for large time behavior where $b(t) \rightarrow b_w$. In Fig. 12, we plot the ratio of b/s as a function of time at s values of 38, 102, 203, and 305 μm for underfill A. Here a clear dependence on s is observed. Generally b/s increases as s decreases. The combined actions of a dynamic wetting angle and nonlinear fluid behavior make the simple Washburn model inadequate to capture the amplitude or time profile shape of the quantity b/s . This is in distinct contrast with behavior exhibited in Fig. 7 for a Newtonian liquid. The non-Newtonian fluid models discussed in the proceeding section of this paper state that μ_{app} should scale with γ_{app} . Recalling that $b/s \sim 1/\mu_{\text{app}}$ Fig. 13 plots the variation of b/s with apparent strain-rate at four s values of 102, 203, 406, and 508 μm . Again the data exhibit a dependence on the channel spacing. However, one should be cautious in prescribing a spacing dependence to the apparent viscosity, based on Fig. 13.

- 1) The evolution of the particle distribution with time may play an important role in setting the apparent viscosity value [10]–[11].
- 2) b/s is also effected by the variation of the θ , which is not independent of s .

Our examinations of a well characterized Newtonian fluid, mineral oil, a model dense suspension, polystyrene spheres in propylene glycol, and of a number of commercial underfill mixtures clearly show that a simple flow model [cf., (1)] provides an inadequate description of the complex flow behavior of these materials. While in a simple Newtonian fluid model [cf., (1)] we would expect the square of the front position to be proportional to time for a planar capillary flow such as underfill, we observe dramatic deviations from linearity. We epitomize this behavior with a metric, the flow parameter, b [cf., (4)]. While in a simple flow model for

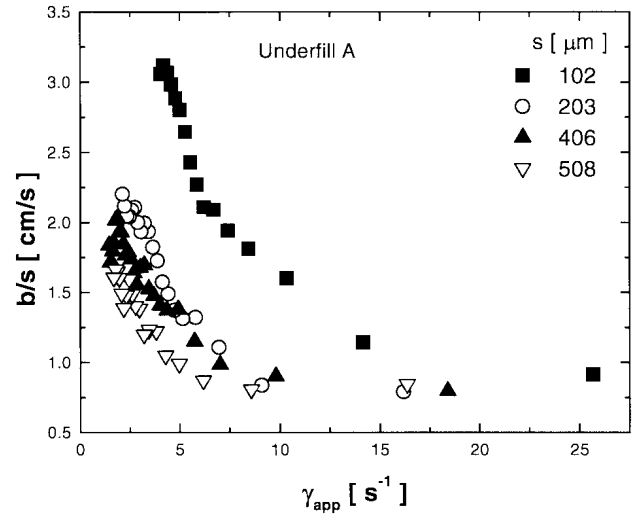


Fig. 13. Plots of the time derivative of the square of the front position divided by the plate spacing as a function of apparent strain rate for commercial underfill A. The underfill underwent flow between parallel glass plates of different spacings, s . All of the flows were at a temperature of 70 °C.

our experiments, b should be a constant, we observe time variations of b . We find for mineral oil that the variation of the contact angle with velocity results in a smaller driving force for flow than expected, and results in a value of b which increases with respect to time, but never quite reaches the value which would be expected on the basis of the simple model (1). The flow parameter, b , is also sensitive to the distinctly nonlinear rheology of dense suspensions, as we found upon examination of the flow behavior of such a dense suspension ($\phi = 0.5$). The time variation of b during flow revealed changes even more dramatic than those due solely to the dynamic contact angle. This variation was interpreted in terms of a shear thickening viscosity of the suspension. Similar, distinct behaviors were found in studies of the capillary parallel plate flow of commercial underfill mixtures. Clear variations of b with respect to time were found. Also, b does not scale linearly with s . We found the flow parameter, b , to be a valuable metric in revealing differences in the flow behaviors of different suspensions, and in revealing dramatic deviations of this flow from that predicted on the basis of a simple model.

IV. CONCLUSION

The flow behavior of commercial underfill mixtures is a complex function of mixture properties, wetting properties, and flow geometries. We have examined plane capillary flow of various fluids, including model suspension, and commercial underfill mixtures. We have defined and explored a metric termed the flow parameter which scales as $\sigma \cos(\theta)/\mu_{\text{app}}$ and provides a sensitive indicator of different flow behaviors. Thus, we have found experimental evidence that both the contact angle, θ , and the apparent suspension viscosity, μ_{app} , vary with time under the influence of changing flow conditions. We have elucidated some of the physical phenomena which render a simple model inadequate in the description of the flow behavior of these suspensions.

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Gary L. Lehmann received the Ph.D. degree in mechanical engineering from Clarkson University, Potsdam, NY.

He is an Associate Professor in the Department of Mechanical Engineering, State University of New York at Binghamton. His publications are in heat transfer and fluid flow with applications in electronic packaging.

T. Driscoll received the B.S. degree in physics from LeMoyne College, Syracuse, NY and the M.S. degree in physics from the State University of New York at Binghamton, where he is currently pursuing the Ph.D. degree in chemical physics.

His research is the flow and rheology of neutrally buoyant dense suspensions.

N. R. Guydosh is an undergraduate chemistry major at Harvard University, Cambridge, MA.

His research has been the rheology and the flow behavior of model suspensions for several years.

P. C. Li received the B.S. degree in applied physics from Tamkang University, Taiwan, R.O.C., and is currently pursuing the M.S. degree in physics at the State University of New York at Binghamton.

His research is in the flow and rheology of model suspensions and commercial encapsulants.

Eric J. Cotts received the Ph.D. degree in physics from the University of Illinois, Urbana.

He is an Associate Professor in the Physics Department, State University of New York at Binghamton. His research interests include diffusion in metal interconnects and the rheology of dense suspensions in systems relevant to electronic packaging.