Theoretical Analysis on Extrusion Die Flow of Electronic Packaging Materials

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A mathematical model has been developed to describe the extrusion die flow of reactive electronic packaging materials. This model assumes that the flow is 1-D in the manifold of the die, but the flow obeys the 2-D Hele−Shaw model in the slot section. A realistic viscosity expression that includes the effects of chemical reaction and heat transfer has been adopted. A linearly tapered coat-hanger die was selected for illustration and the packaging material was chosen to be the epoxy system. Some example calculations are presented to illustrate the effects of several parameters on the flow distribution. Two optimization approaches were adopted to improve the uniformity of the flow; both the Taguchi method and the method of inserting a specially designed choker bar are applicable. However, using a choker bar appears to be more effective and flexible.

Introduction

Many electronic packaging materials are made by precision coating processes. These materials are usually in the form of thin films or tapes. For example, films that serve as insulation in tape automated bonding (TAB) (Lau et al., 1990), flexible printed circuit boards (FPC) (Gilleo, 1992), or tape ball grid array (T-BGA) (Lau, 1995), to name a few, are made by precision coating of materials on specific polymer film bases. The materials usually involve various polyimide (Imaizumi et al., 1992) or epoxy (Hirrekorn and Emmons, 1990) systems. One of the important requirements for these insulation films or tapes is that the thickness be uniform; otherwise, the insulation effect will be jeopardized. For example, if the film thickness of FPC with typical circuitry varies 10%, the impedence will vary 14% (Tummala et al., 1989) and the internal stress under thermal cyclings will vary 10% (Lau, 1993). Control of the coating film is therefore critical to these materials.

It is generally agreed that extrusion slot coating is an effective means for making electronic packaging films. The discussion of this coating method can be found in several recently published books (Cohen and Gutoff, 1992; Gutoff and Cohen, 1995; Kistler and Schweizer, 1997), and the coating windows for this method were examined both theoretically and experimentally (Ruschak, 1976; Higgins and Scriven, 1980; Lee et al., 1992; Yu et al., 1995; Ning et al., 1996).

To carry out extrusion slot coating successfully, the extrusion die has to be properly designed and constructed so that a uniform liquid sheet can emanate from the die's slot exit and deposit on the polymer substrate.

Theoretical studies on the design of extrusion dies have been extensive; however, most work has focused on nonreactive polymeric liquids. Only a few technical articles examined the design and performance of extrusion die for the reactive materials. Debry et al. (1986) and Charbonneaux (1988) studied the film extrusion of thermosetting materials and found that significant buildup on the interior wall of the extrusion die may occur if the gel point is exceeded. More recently Pan et al. (1997) analyzed the extrusion die flow for slowly reacting materials; they assumed that the fluid viscosity was time-dependent and the reaction rate was slow, so they extended the popular lubrication theory for nonreactive fluids to the reactive systems.

For electronic packaging materials such as polyimide or epoxy systems, reaction may occur inside the extrusion die. It

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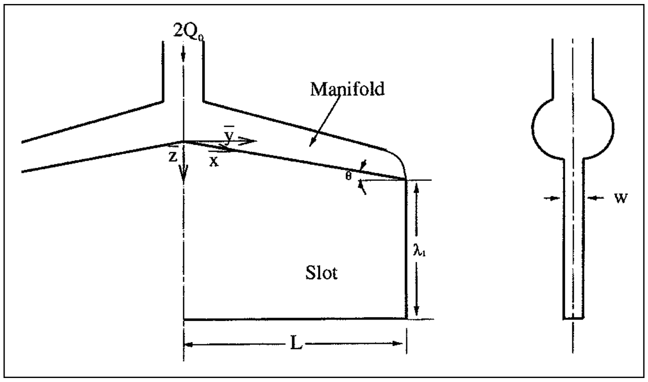

Figure 1. Geometry of a linearly tapered coat-hanger die.

is possible to prevent the chemical reaction by lowering the die temperature, using a smaller amount of additive, or adding inhibitors; however, if these measures are taken, the selection of solvent systems or additives will be limited, and reducing the die temperature will increase the product cost. Therefore it is advantageous to develop a mathematical model that can predict the extrusion die flow with chemical reaction accurately, so that the uniformity of the liquid film at the slot exit of the die can be properly controlled.

This article extends the work of Pan et al. (1997) to develop a complex mathematical model that can describe the extrusion die flow with chemical reaction more realistically. Two approaches to improve the flow uniformity are also studied.

Mathematical Formulation

The extrusion die we study is a linearly tapered coat-hanger die, as shown in Figure 1; owing to symmetry, we only consider the right-half of the die. A coordinate system can be imposed as shown in Figure 1; here the $\bar{x}$-axis coincides with the straight edge of the tapered manifold, the $\bar{y}$-axis represents the cross-machine direction, and the $\bar{z}$-axis represents the machine direction. The angle between the slot section and the edge of the manifold is θ.

In practice the slot gap is usually much smaller than the characteristic length of the manifold, so we may assume that the mainstream in the manifold is a one-dimensional (1-D) flow, and moves from the center toward the end of the manifold. On the other hand, the flow in the slot section basically follows the 2-D Hele−Shaw model, as in the case of reaction injection molding (Garcia et al., 1991). The following assumptions are also necessary for the mathematical model:

1. The chemical reaction is not fast enough, so the flow is steady and locally fully developed in the manifold.
2. The fluid is incompressible.
3. The viscous effect is the dominant factor, so the effects of gravity and fluid inertia can be neglected. The entrance and end effects are also negligible.
4. Since the diffusion coefficients for polymeric liquid systems are small, the effect of molecular diffusion is neglected.
5. The solution inside the die is assumed to be Newtonian, owing to low degree of conversion.
6. There is no significant temperature rise, so the thermal properties of the fluids can be assumed to be constant.
7. Heat transfer through conduction in the flow direction can be neglected.

All of these assumptions are reasonable, based on true material properties. For reactive materials such as epoxy systems, the fluid viscosity η can be expressed as (Halley and Mackay, 1996)

$$\eta = \eta_0 \left[\frac{\alpha_g}{\alpha_g - \alpha} \right]^{a + b\alpha}. \tag{1}$$

The reference viscosity η_0 is a function of temperature, that is,

$$\eta_0 = K e^{-\beta(\overline{T} - T_0)}. \tag{2}$$

Therefore,

$$\eta = K \left[\frac{\alpha_g}{\alpha_g - \alpha} \right]^{a + b\alpha} e^{-\beta(\overline{T} - T_0)}. \tag{3}$$

For the epoxy system, the reaction rate usually can be expressed as (Halley and Mackay, 1996)

$$R/C_0 = d\alpha/dt = \left(k_1 + k_2 \alpha^{m1}\right)(1 - \alpha)^{m2} \tag{4}$$

$$k_1 = k_{10} e^{[-E_1/(R_g \overline{T})]}, \qquad k_2 = k_{20} e^{[-E_2/(R_g \overline{T})]}. \tag{5}$$

On the basis of the preceding assumptions, the pressure drop/flow rate equation in the manifold is as follows (Liu, 1983):

$$\overline{Q} = \frac{\lambda \overline{h}^4}{\eta} \left(-\frac{d\overline{P}}{d\bar{x}} \right). \tag{6}$$

Here λ is a shape factor and its value can be found elsewhere (Liu, 1983).

Substituting Eq. 3 into Eq. 6,

$$\overline{Q} = \frac{\lambda \overline{h}^4}{K\left[\alpha_g/(\alpha_g - \alpha)\right]^{(a + b\alpha)} e^{-\beta(\overline{T} - T_0)}} \left(-\frac{d\overline{P}}{d\bar{x}} \right). \tag{7}$$

The conservation of species in the manifold is

$$\overline{Q} \frac{d\alpha}{d\bar{x}} - \overline{h}^2 \left(k_1 + k_2 \alpha^{m1}\right)(1 - \alpha)^{m2} = 0. \tag{8}$$

The energy balance equation in the manifold is

$$\rho C_p \overline{Q} \frac{d\overline{T}}{d\bar{x}} - h_m \bar{x} \left[\overline{T}_w - \overline{T}\right] - \overline{h}^2 R \Delta H = 0, \tag{9}$$

with

$$R = -\frac{dC}{dt} = C_0 \frac{d\alpha}{dt}. \tag{10}$$

Since the Hele−Shaw model is assumed to be valid for flow in the slot section, the following governing equations are introduced:

$$\frac{\partial \bar{q}_{\bar{y}}}{\partial \bar{y}} + \frac{\partial \bar{q}_{\bar{z}}}{\partial \bar{z}} = 0 \tag{11}$$

$$\bar{q}_{\bar{y}} = \frac{2}{3}\left(\frac{\partial \bar{P}}{\partial \bar{y}}\right)\frac{w^3}{K\left[\alpha_g/(\alpha_g - \alpha)\right]^{(a+b\alpha)}} \tag{12}$$

$$\bar{q}_{\bar{z}} = \frac{2}{3}\left(\frac{\partial \bar{P}}{\partial \bar{z}}\right)\frac{w^3}{K\left[\alpha_g/(\alpha_g - \alpha)\right]^{(a+b\alpha)}} \tag{13}$$

$$\bar{q}_{\bar{y}}\frac{d\alpha}{d\bar{y}} + \bar{q}_{\bar{z}}\frac{d\alpha}{d\bar{z}} - w\left(k_1 + k_2\alpha^{m1}\right)(1-\alpha)^{m2} = 0 \tag{14}$$

$$\rho C_p \bar{q}_{\bar{y}}\frac{\partial \bar{T}}{\partial \bar{y}} + \rho C_p \bar{q}_{\bar{z}}\frac{\partial \bar{T}}{\partial \bar{z}} - 2h_s\left[\bar{T}_w - \bar{T}\right] - wR\Delta H = 0. \tag{15}$$

Since the loss of flow in the manifold is equal to the amount that enters the slot section, the following material balance equation is used:

$$\frac{d\bar{Q}}{d\bar{y}} = -\bar{q}. \tag{16}$$

Here $\bar{q} = \sqrt{\bar{q}_{\bar{x}}^2 + \bar{q}_{\bar{y}}^2}$ is the volumetric flow rate per unit die width. The flow distribution at the slot exit can be represented by $\bar{q}$. The following dimensionless variables are defined as:

$$Q = \bar{Q}/Q_0, \qquad (x,y,z) = (\bar{x},\bar{y},\bar{z})/L,$$
$$(q, q_y, q_z) = \left(\bar{q}, \bar{q}_{\bar{y}}, \bar{q}_{\bar{z}}\right)/(Q_0/L)$$
$$h = \bar{h}/h_0, \qquad h_0 = \left(Lw^3/(12\lambda \sin\theta)\right)^{1/4}$$
$$P = \bar{P}/P_0, \qquad P_0 = 3KQ_0/(2w^3), \qquad T = \left(\bar{T} - T_0\right)/T_0 \tag{17}$$

After substituting the dimensionless variables into the preceding governing equations,

(I) Manifold

$$Q = \frac{A_v h^4}{\left[\alpha_g/(\alpha_g-\alpha)\right]^{(a+b\alpha)} e^{e^{-\beta T_0 T}}}\left(-\frac{dP}{dx}\right) \tag{18}$$

$$Q\frac{d\alpha}{dx} - D_{am}h^2\frac{C_0}{R_0}\left(k_1 + k_2\alpha^{m1}\right)(1-\alpha)^{m2} = 0 \tag{19}$$

$$Q\frac{dT}{dx} - \frac{N_{um}}{G_z}\frac{s}{r_n}\left[\frac{T_w - T_0}{T_0} - T\right] - \frac{P_{em}}{G_z}\frac{C_0}{R_0}\left(k_1 + k_2\alpha^{m1}\right)[1-\alpha]^{m2} = 0, \tag{20}$$

with

$$A_v \equiv \frac{\lambda h_0^4}{Lw^3}\left(\frac{3}{2}\right); \qquad D_{am} \equiv \frac{h_0^2 L R_0}{Q_0 C_0}$$
$$N_{um} \equiv \frac{h_m r_n}{k_c}; \quad P_{em} \equiv \frac{\Delta H R_0 h_0^2}{k_c T_0}; \quad G_z \equiv \frac{\rho C_p Q_0}{k_c L} \tag{21}$$

(II) Slot section

$$\frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \tag{22}$$

$$q_y = \left(\frac{\partial P}{\partial y}\right)\frac{1}{\left[\alpha_g/(\alpha_g-\alpha)^{a+b\alpha}\right]e^{-\beta T T_0}} \tag{23}$$

$$q_z = \left(\frac{\partial P}{\partial z}\right)\frac{1}{\left[\alpha_g/(\alpha_g-\alpha)^{a+b\alpha}\right]e^{-\beta T T_0}} \tag{24}$$

$$q_y\frac{\partial\alpha}{\partial y} + q_z\frac{\partial\alpha}{\partial z} - D_{as}\frac{C_0}{R_0}\left(k_1 + k_2\alpha^{m1}\right)(1-\alpha)^{m2} = 0 \tag{25}$$

$$q_y\frac{\partial T}{\partial y} + q_z\frac{\partial T}{\partial z} - \frac{2N_{us}}{G_z}\frac{L}{w}\left[\frac{T_w - T_0}{T_0} - T\right] - \frac{P_{es}}{G_z}\frac{C_0}{R_0}\left[k_1 + k_2\alpha^{m1}\right][1-\alpha]^{m2} = 0, \tag{26}$$

with

$$D_{as} \equiv \frac{L^2 w R_0}{Q_0 C_0}; \quad P_{es} \equiv \frac{\Delta H R_0 L w}{k_c T_0}; \quad N_{us} \equiv \frac{h_s w}{k_c}. \tag{27}$$

The material balance equation becomes

$$dQ/dy = -q. \tag{28}$$

It is assumed that at the die entrance, $y = 0$, the inlet volumetric flow rate and temperature can be specified. If catalysts and curing agents are injected just before the fluid enters the die, the initial conversion can be set as zero; otherwise, the conversion α should be detected at the die entrance, and the detected value is the initial conversion. Mathematically, there is no difficulty in solving the model with different values of α. We therefore set α as zero for illustration. At $y = 1$, there is no outflow, and at the slot exit the fluid pressure should be atmospheric, so the required boundary conditions are

(i) $Q = 1$, $T = 0$, and $\alpha = 0$ at $y = 0$.
(ii) $Q = 0$ at $y = 1$.
(iii) At outlet, $P = 0$.
(iv) At the wall plane of symmetry, $\partial P/\partial y = 0$. (29)

It should be noted that a general mathematical model was developed. Since the heat-transfer coefficient for the flow

Table 1. Geometric Parameters of the Coat-Hanger Die for Illustration

Parameters	Dimension
L	30 cm
θ	1°
λ_1	4 cm
h_0	0.41 cm
x_0^*	0
w	0.02 cm
ad*	0.25

$^*h = h_0(1 - x + x_0)^{ad}$.

Table 3. Values of the Dimensionless Groups in Terms of k_1, Q_0, and ΔH

Dimensionless Group	Definition	Values in Terms of k_1, Q_0, and ΔH	Typical Range*
D_{am} (Damkohler number for manifold)	$h_0^2 LR_0/Q_0C_0$	$5.043\ k_1/Q_0$	0.02–0.15
D_{as} (Damkohler number for slot)	$L^2 wR_0/Q_0C_0$	$18\ k_1/Q_0$	0.06–0.54
P_{em} (Peclet number for manifold)	$\Delta HR_0 h_0^2/k_cT_0$	$0.332\ k_1\Delta H$	0.03–0.30
P_{es} (Peclet number for slot)	$\Delta HR_0 Lw/k_cT_0$	$1.184\ k_1\Delta H$	0.12–1.07
G_z (Graetz number)	$\rho C_p Q_0/k_c L$	$36.1\times Q_0$	36.1–108

$^*Q_0 \sim 1–3\ cm^3/s$, $k_1 \sim 0.01–0.03\ sec^{-1}$, $\Delta H \sim 10–30$ J/g.

system is difficult to evaluate, we examine two limiting cases for heat transfer inside the die: the isothermal case represents the condition of perfect heat transfer, while the adiabatic case represents no heat transfer between the fluid and the wall of the die body. The energy equation is not considered for the isothermal condition. As for the adiabatic condition, the boundary condition on the wall is $\partial T/\partial n = 0$. The real situation should be between these two limiting cases.

The preceding governing equations with corresponding boundary conditions can be solved numerically by the finite-element method (Wen et al., 1994; Wen and Liu, 1995) with slight modifications. Some interesting example calculations are presented in the next section.

Example Calculations

We illustrate the application of the present mathematical model by some example calculations. The dimensions of the linearly tapered coat-hanger die displayed in Figure 1 are given in Table 1. This die was the same as the one examined by Pan et al. (1997), and the dimensions were chosen such that a uniform liquid sheet could be delivered for a fluid with no chemical reaction. Some required physical properties of the fluid are given in Table 2 (Keenan, 1987; May, 1988).

There are several dimensionless groups that appear in the mathematical model that influence the flow distributions at the slot exit. Instead of examining the effect of each group on the flow distributions, we focus only on three parameters—the reaction constant k_1, which controls the reaction rate; the inlet flow rate Q_0, which controls the residence time distribution; and the reaction heat ΔH, which controls the temperature variation—because these variables are adjustable, and in practice they can be varied to improve the flow distributions. After substituting the parameters in Tables 1 and 2 into these groups, they can be expressed as functions of k_1, Q_0, and ΔH. The results are presented in Table 3. We examine the effects of varying k_1, Q_0, and ΔH on the flow distributions at the slot exit.

We now examine the cases of varying k_1 and Q_0 for isothermal flow. The effect of the reaction constants k_1 and k_2 on the flow distributions at the slot exit is shown in Figure 2. As the reaction constant increases, the flow uniformity deteriorates. This is because a larger reaction constant will accelerate the chemical reaction and cause the fluid viscosity to increase much faster. The conversion data corresponding to the three cases in Figure 2 at the slot exit indicate that a larger reaction constant will yield higher conversion, particularly near the end of the manifold, where the residence time of the fluid is longer.

The effect of the inlet volumetric flow rate Q_0 on the flow distributions is given in Figure 3. If the flow rate is higher, the residence time for fluid inside the die is shorter, so the

Table 2. Physical Properties of the Epoxy System for Illustration

Parameter	Unit	Value
ρ	g/cm^3	1.2
C_p	J/(g K)	1.533
k_c	J/(cm K s)	1.7×10^{-3}
ΔH	J/g	~10–30
C_0	g/cm^3	1.0
R_0	$g/(cm^3\ s)$	$1.0\times k_1$
T_0	K	300
a	—	1
b	—	1
$m1$	—	1
$m2$	—	1
η_0	(g/cm s)	0.1

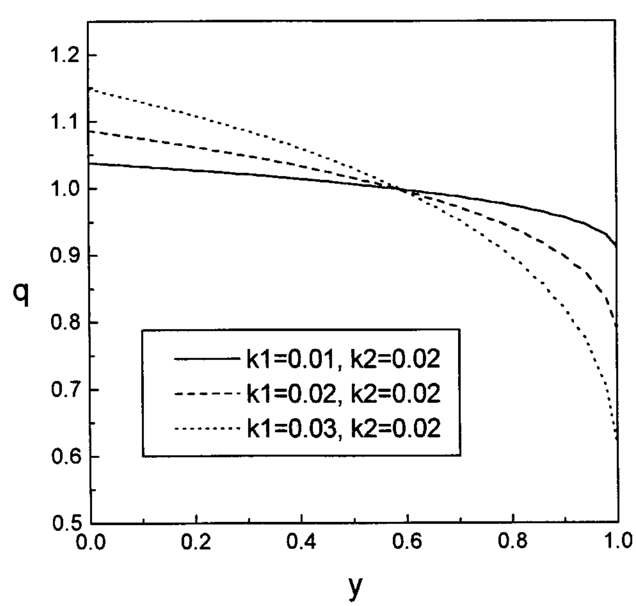

Figure 2. The effect of the reaction constants k_1 and k_2 on the flow distributions at the slot exit; $Q_0 = 1$.

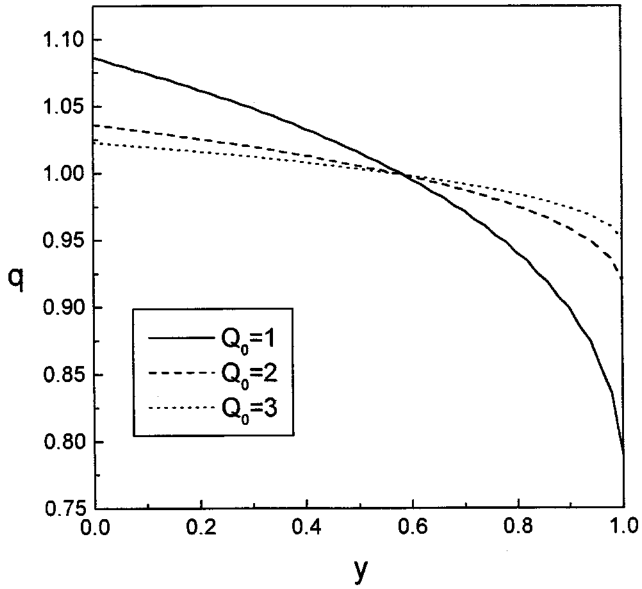

Figure 3. The effect of the inlet volumetric flow rate Q_0 on the flow distributions at the slot exit; $k_1 = 0.02$, $k_2 = 0.02$.

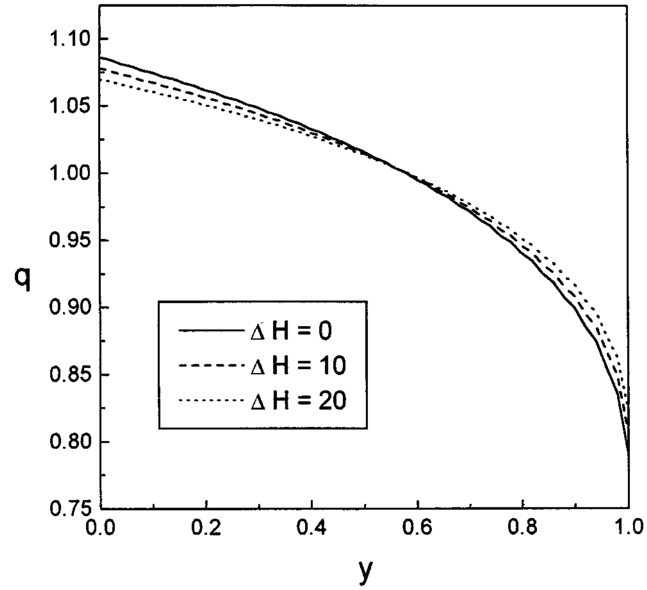

Figure 4. The effect of the reaction heat ΔH on the flow distributions at the slot exit; $Q_0 = 1$, $k_1 = 0.01$, $k_2 = 0.02$, $\beta = 0.02$.

reaction is less complete and the fluid viscosity variation is not as significant as the case with a lower flow rate. The trend of conversion is predictable, so the results will not be presented here.

As for the adiabatic operating condition, we examine the effect of the reaction heat ΔH. After examining the fluid temperature distributions at the slot exit, it is found that increasing ΔH will only cause the fluid temperature to rise slightly, particularly at the die end. The results in Figure 4 indicate that the effect of increasing ΔH on the flow distributions is less important. Basically the reaction heat for the epoxy system in this study is not significant, so we can conclude that if the physical properties of the fluid and the operating conditions are close to those contained in Tables 2 and 3, the assumption of isothermal flow is reasonable.

It is obvious that the flow distributions presented in Figures 2 and 3 are not acceptable. From the production viewpoint, the variation in the film thickness should usually be within 5%. Thus the key question is how to improve the flow distributions to an acceptable level. We examine two approaches that can improve the flow distribution.

The first method we apply to improve the flow distributions is the Taguchi method (Roy and Taguchi, 1990). To apply the Taguchi method, we need to design an observation value and then select a group of parameters. By examining the sensitivity of each parameter on the observation value, a combination of a few parameters can be selected to optimize the observation value.

For our case, the observation value Y is designed as:

$$Y = \frac{q_{\max} - q_{\min}}{q_{\max}} \times 100, \tag{30}$$

where $q_{\max}$ and $q_{\min}$ are the maximum and minimum flow rates per unit die width at the slot exit. If the perfect flow distribution is reached, $Y = 0$. The value $(1 - Y)$ can be viewed as an indicator of flow uniformity.

We examine the sensitivity of six parameters, and three different levels (values) are selected for each parameter. The parameters and the values of the three levels for each parameter are listed in Table 4.

With the values available in Table 4, Y can be computed by solving the mathematical model repeatedly. The results of eighteen cases are given in Table 5.

The sensitivity of each parameter on the flow distributions can now be determined. The sensitivity S_{ij} for each parameter can be computed with $i = A, B, C, D, E, F$ and $j = 1, 2, 3$. For example, if Case A corresponds to the parameter ad, then

$$S_{A1} = \frac{57.3 + 28.1 + 39.1 + 60 + 15.7 + 89.4}{6} = 48.2 \tag{31}$$

$$S_{A2} = \frac{22.5 + 77.7 + 83.6 + 20.4 + 100 + 14.8}{6} = 53.2 \tag{32}$$

$$S_{A3} = \frac{36.4 + 43.8 + 18.1 + 100 + 2.6 + 17.6}{6} = 36.4. \tag{33}$$

Table 4. Values of Each Parameter and Level

Case	Parameter	Level 1	Level 2	Level 3
A	ad	0.125	0.25	0.5
B	θ	1°	2°	3°
C	w	0.01 cm	0.02 cm	0.03 cm
D	λ_1	2 cm	4 cm	6 cm
E	x_0	0	0.1	0.2
F	h_0	0.15 cm	0.27 cm	0.41 cm

Table 5. Geometric Parameters of the Coat-Hanger Die and the Y Value

Die	Parameters ad	θ	w	λ_1	x_0	h_0	Y
1	1	1	1	1	1	1	57.3
2	1	2	2	2	2	2	28.1
3	1	3	3	3	3	3	39.1
4	2	1	1	2	2	3	22.5
5	2	2	2	3	3	1	77.7
6	2	3	3	1	1	2	83.6
7	3	1	2	2	3	2	36.4
8	3	2	3	1	1	3	43.8
9	3	3	1	3	2	1	18.1
10	1	1	3	3	2	2	60.0
11	1	2	1	1	3	3	15.7
12	1	3	2	2	1	1	89.4
13	2	1	2	3	1	3	20.4
14	2	2	3	1	2	1	100*
15	2	3	1	2	3	2	14.8
16	3	1	3	2	3	1	100*
17	3	2	1	3	1	2	2.6
18	3	3	2	1	2	3	17.6

*q_{min} is close to zero before the end of the die, so Y is set to be 100.

Table 6 lists the values of S_{ij} for the six parameters; the cases with lower S_{ij} are more favorable. S_{C1} appears to be the lowest, which implies that by reducing the slot gap w, the flow uniformity can be improved most effectively. It is also observed that S_{F3} is relatively small, so by enlarging the cross-sectional area of the manifold at the die entrance, the flow uniformity can be improved. Enlarging the manifold will reduce the flow rates, however, and once a critical value of h_0 is reached, its effect will be reversed. Three example calculations are presented in Table 7. In these cases the dimensions of the die are selected following data in Table 1 and the reaction parameters are varied. The flow uniformity is not acceptable before changing any geometric parameter; however, by reducing w from 0.02 cm to 0.01 cm, and by fine-tuning the die angle θ, the flow uniformity can be significantly improved. The reason for selecting θ for fine-tuning is because the data in Table 6 indicate that it is the least sensitive parameter to flow uniformity.

It should be mentioned that even if reducing the slot gap w can be an effective means of improving the flow uniformity, the pressure inside the die will also increase significantly. The data in Table 7 indicate that if the slot gap reduces 50%, the flow uniformity is improved satisfactorily; however, the pressure will be seven times higher, which may cause mechanical distortion of the die body and other production problems.

We can also improve the flow uniformity by inserting a specially designed choker bar into the slot section. This choker bar usually has a rectangular cross section. The idea of using a flexible choker bar was first proposed by Wu and Liu (1994), and it was also adopted by Pan et al. (1997) for slowly reacting systems. The choker bar we propose to insert is displayed in Figure 5, and consists of a thicker part and a thinner part. The boundary between the two parts is a shape function $\lambda_2(y)$ that is yet to be determined by the optimization procedure to improve the flow uniformity. For illustration, we consider a case with an uneven flow distribution, as shown by the solid line in Figure 6. If a regular choker bar with a rectangular cross section is inserted, we find that the flow distribution only varies slightly, as the dotted line in Figure 6 indicates. This is quite interesting, because a regular choker bar is usually helpful for nonreactive flow systems (Wu et al., 1995). For a reactive system, the regular choker bar can only reduce the fluid's residence time, but it cannot vary the residence time distribution; therefore, the flow distributions that depend heavily on the degree of reaction will not be affected.

Table 6. Sensitivity of Different Parameters

i (item)	j (level) 1	2	3
S_{ij}			
A	48.2	53.2	36.4
B	49.4	44.6	43.8
C	21.8	44.9	71.1
D	52.9	48.5	36.4
E	49.5	41.1	47.2
F	70.1	37.6	27.4

We can adopt the approach of Chiou et al. (1998) to design a choker bar that can improve the flow distribution. The uneven flow distribution, as represented by the solid curve in Figure 6, indicates that higher flow rates appear in the central area of the die; therefore, a choker bar should be designed to create a higher resistance for flow in the central region. Since the solid curve appears to be smooth, we can assume that the resistance should be smoothly created. The design procedure is as follows:

1. We assume that the taper function $\lambda_2(y)$ of the special choker bar has the form of a polynomial, as shown in Figure 5, and we select a fourth-order polynomial for illustration:

$$\lambda_2(y) = 1 + a_1 y + a_2 y^2 + a_3 y^3 + a_4 y^4, \tag{34}$$

where the coefficients a_i are determined through an optimization procedure. The initial guesses of a_i are obtained by approximating the flow distributions of the solid line in Figure 6.

2. We define an objective function F as follows:

$$F \equiv \int (q-1)^2 \, dy. \tag{35}$$

Table 7. Optimal Die Design for Different Reaction Systems by the Taguchi Method

Reaction System	Reaction Parameters k_1	k_2	$m1$	$m2$	a	b	Geometric Parameters L	w	θ	λ_1	h_0	x_0	ad	Uniformity	Uniformity Before Varying w and θ
A	0.02	0.02	2	2	1	1	30	0.01	7	4	0.15	0	0.25	0.992	0.798
B	0.02	0.02	1	1	1	1	30	0.01	7	4	0.15	0	0.25	0.992	0.748
C	0.02	0.02	2	2	2	2	30	0.01	8	4	0.15	0	0.25	0.988	0.588

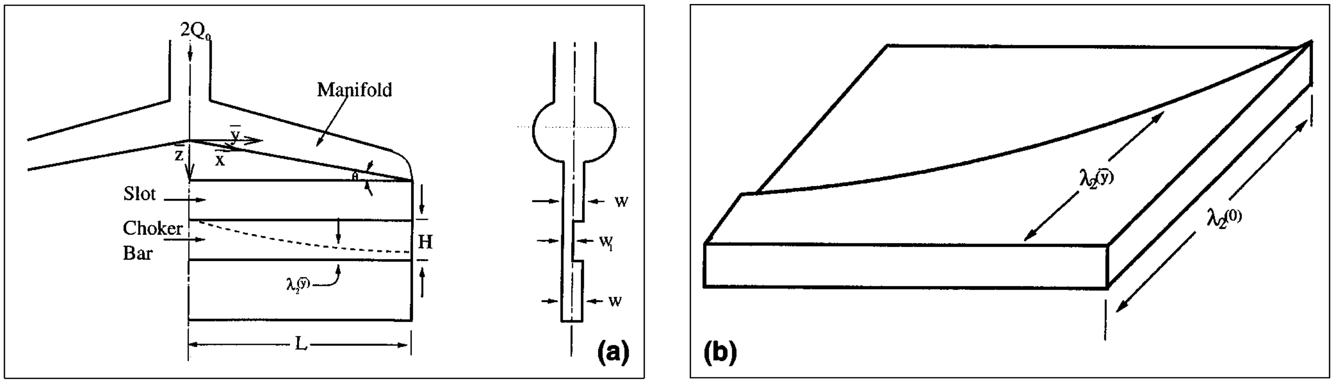

Figure 5. A linearly tapered coat-hanger die with an adjustable choker bar.

(a) Overall geometry; (b) choker bar and the shape function $\lambda_2(\bar{y})$.

Once the initial profile of $\lambda_2(y)$ is obtained, the mathematical model is solved to determine the flow distribution q.

3. An optimization code is called the Hooke algorithm (Kuester and Mize, 1973). A new set of a_i is searched to minimize F. This procedure is repeated until the optimal values of a_i are found. Once F approaches zero, the flow distribution will be uniform.

The optimal values in Eq. 34 are found as follows:

$$\lambda_{2,II}(y) = 1 + 0.0133y - 0.7584y^2 + 1.2715y^3 - 0.8786y^4. \tag{36}$$

With $\lambda_2(y)$ determined, we again solve the mathematical model to determine the flow distribution q. The results are displayed in Figure 6. It is clear that by choosing a specially designed choker bar, the flow distribution can be improved effectively. It should be noted that inserting an optimal choker bar will also increase the pressure inside the die; however, the pressure will only be two times higher, much lower than the cases based on the Taguchi method. Therefore we can conclude that inserting a specially designed choker bar can be an effective means for improving the flow uniformity. For a different system, another specially designed choker bar can be inserted without altering the basic die geometry.

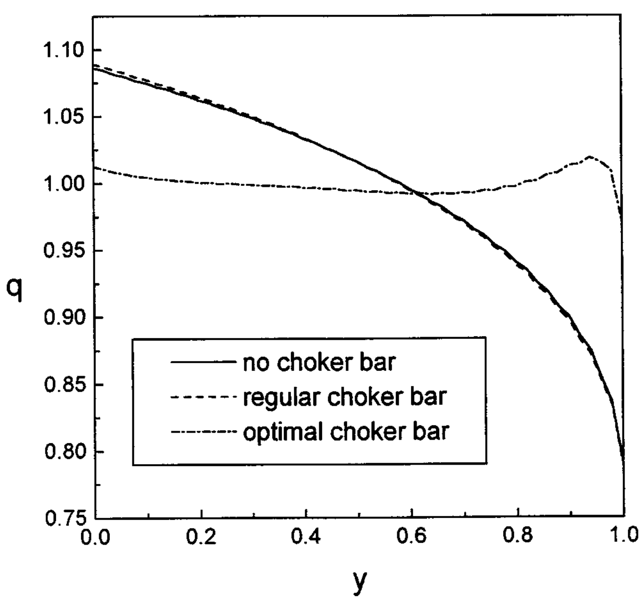

Figure 6. The effect of choker bars on the flow distributions at the slot exit; $Q_0 = 1$, $k_1 = 0.02$, $k_2 = 0.02$.

For the regular choker bar, $H = 1$ cm, $w_1 = 0.5$ W. For the optimal choker bar, $\lambda_2(0) = 1$ cm, $w_1 = 0.5$ W.

Conclusion

We have presented a mathematical model to describe the extrusion die flow of reactive electronic packaging materials. The extrusion die we used for illustration is a linearly tapered coat-hanger die. The mathematical model assumes that the flow is one-dimensional (1-D) in the manifold and that the 2-D Hele−Shaw model is valid for flow in the slot section. The viscosity expression includes the effects of chemical reaction and heat transfer.

Some example calculations were carried out to demonstrate the applicability of the model, and the epoxy system was adopted for illustration. The effects of three parameters, namely, the reaction constant, the inlet flow rate, and the reaction heat on the flow distributions, were examined. For the epoxy system studied, the effect of reaction heat is less important, so the assumption of isothermal flow is reasonable.

The flow uniformity deteriorates rapidly for systems with chemical reaction. Two approaches were adopted to improve the flow distributions: the Taguchi method was studied first and the sensitivity of six parameters on the flow uniformity was examined, with the slot gap appearing to be the most sensitive parameter. By reducing the slot gap, the flow distribution can be significantly improved. However, reducing the slot gap will cause a tremendous increase in pressure inside the die, which may be a negative factor for practical design and operation.

The other approach is to insert a specially designed choker bar into the slot section. The choker bar is designed so that higher resistance will be created for areas with higher flow rates. Through the help of the Hooke algorithm, an optimization procedure was carried out to select the shape function of the choker bar.

The shape function under study was assumed to be a fourth-order polynomial, and the coefficients of the polynomial were determined through the optimization procedure. It was found that the specially designed choker bar can effectively improve the flow uniformity. So inserting a specially designed choker bar in the slot section appears to be an effective and flexible means of delivering a unform liquid sheet with reaction.

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Notation

a, b = constants, Eq. 1
C = epoxy concentration
C_0 = inlet epoxy concentration
C_p = heat capacity of the fluid
E_1, E_2 = activation energies, Eq. 5
ΔH = reaction heat
$\bar{h}, h$ = square root of the cross-sectional area of the manifold, dimensional and dimensionless
h_0 = square root of the cross-sectional area at the die entrance
h_m, h_s = heat-transfer coefficients in the manifold and in the slot section, respectively
K = constant, Eq. 2
K_c = thermal conductivity
k_1, k_2 = reaction constants, Eq. 4
K_{10}, K_{20} = constants, Eq. 5
L = one-half of the die width
$m1, m2$ = constants, Eq. 4
n = direction normal to the wall
$\bar{P}, P$ = fluid pressure, dimensional and dimensionless
$\bar{Q}, Q$ = volumetric flow rate, dimensional and dimensionless
Q_0 = inlet volumetric flow rate
$\bar{q}_y, \bar{q}_z$ = volumetric flow rates per unit die width in the y and z directions, respectively
r_n = hydraulic radius of the manifold
R = reaction rate
R_0 = initial reaction rate
R_g = gas constant
$\bar{S}$ = wetted perimeter of the manifold
$\bar{T}, T$ = fluid temperature, dimensional and dimensionless
T_0 = reference temperature
$\bar{T}_w, T_w$ = wall temperature, dimensional and dimensionless
t = time
w = slot gap
x_0 = manifold enlargement factor, Table 1

Greek letters

α = reaction conversion
α_g = reaction conversion at gel point
β = constant in Eq. 2
ρ = fluid density

Literature Cited

Charbonneaux, T. G., ''Continuous Reactive Processing of Crosslinkable Monomers: Application to Reactive Coating and Profile Extrusion,'' PhD Diss., Univ. of Minnesota, Minneapolis (1988).

Chiou, J. Y., P. Y. Wu, and T. J. Liu, ''An Integrated Analysis for a Coextrusion Process,'' *Poly. Eng. Sci.*, **38**, 49 (1998).

Cohen, E. D., and E. B. Gutoff, *Modern Coating and Drying Technology*, VCH, New York (1992).

Debry, H. G., T. G. Charbonneaux, and C. W. Macosko, ''Laminar Flow of a Thermosetting Polymer through a Coat-hanger Die,'' *Polym. Process. Eng.*, **4**, 151 (1986).

Garcia, M. A., C. W. Macosko, S. Subbiah, and S. I. Guceri, ''Modeling of Reactive Filling in Complex Cavities,'' *Intern. Polymer Process.*, **VI**, 73 (1991).

Gilleo, K., *Handbook of Flexible Circuits*, Van Nostrand Reinhold, New York (1992).

Gutoff, E. B., and E. D. Cohen, *Coating and Drying Defects*, Wiley, New York (1995).

Halley, P. J., and M. E. Mackay, ''Chemorheology of Thermosets—An Overview,'' *Poly. Eng. Sci.*, **36**, 593 (1996).

Higgins, B. G., and L. E. Scriven, ''Capillary Pressure and Viscous Pressure Drop Set Bounds on Coating Bead Operability,'' *Chem. Eng. Sci.*, **35**, 673 (1980).

Hirrekorn, F. J., and W. D. Emmons, ''*In Situ* Cyclopolymerized Vinyl Anhydride in Polyepoxide,'' U.S. Patent No. 4,946,875 (1990).

Imaizumi, J., H. Nomura, K. Nagao, K. Sakairi, and E. Satou, ''Heat Resistant Adhesive Composition and Bonding Method Using the Same,'' U.S. Patent No. 5,089,346 (1992).

Keenan, M. R., ''Autocatalytic Cure Kinetics from DSC Measurements: Zero Initial Cure Rate,'' *J. Appl. Poly. Sci.*, **33**, 1725 (1987).

Kistler, S. F., and P. M. Schweizer, eds., *Liquid Film Coating*, Chapman & Hall, London (1997).

Kuester, J. L., and J. H. Mize, *Optimization Techniques with Fortran*, McGraw-Hill, New York (1973).

Lau, J. H., S. J. Erasmus, and D. E. Rice, ''Overview of Tape Automated Bonding Technology,'' *Circuit World*, **16**, 2 (1990).

Lau, J. H., *Thermal Stress and Strain in Microelectronics Packaging*, Van Nostrand Reinhold, New York (1993).

Lau, J. H., *Ball Grid Array Technology*, McGraw-Hill, New York (1995).

Lee, K. Y., L. D. Liu, and T. J. Liu, ''Minimum Wet Thickness of Extrusion Slot Coating,'' *Chem. Eng. Sci.*, **47**, 1703 (1992).

Liu, T. J., ''Fully Developed Flow of Power-Law Fluids in Ducts,'' *Ind. Eng. Chem. Fundam.*, **22**, 183 (1983).

May, C. A., *Epoxy Resins*, Marcel Dekker, New York (1988).

Ning, C. Y., C. C. Tsai, and T. J. Liu, ''The Effect of Polymer Additives on Extrusion Slot Coating,'' *Chem. Eng. Sci.*, **51**, 3289 (1996).

Pan, J. P., P. Y. Wu, and T. J. Liu, ''Extrusion Die Design for Slowly Reacting Materials,'' *Poly. Eng. Sci.*, **37**, 856 (1997).

Roy, R. K., and G. Taguchi, *A Primer on the Taguchi Method*, Van Nostrand Reinhold, New York (1990).

Ruschak, K. J., ''Limiting Flow in a Pre-Metered Coating Device,'' *Chem. Eng. Sci.*, **31**, 1057 (1976).

Tummala, R. R., and E. J. Rymaszewski, *Microelectronics Packaging Handbook*, Van Nostrand Reinhold, New York (1989).

Wen, S. H., T. J. Liu, and J. D. Tsou, ''Three-Dimensional Finite Element Analysis of Polymeric Fluid in an Extrusion Die: I. Entrance Effect,'' *Poly. Eng. Sci.*, **34**, 1827 (1994).

Wen, S. H., and T. J. Liu, ''Extrusion Die Design for Multiple Stripes,'' *Poly. Eng. Sci.*, **35**, 759 (1995).

Wu, P. Y., and T. J. Liu, ''Design of an Extrusion Die with a Flexible Choker Bar,'' *J. Appl. Poly. Sci.*, **51**, 1005 (1994).

Wu, P. Y., L. M. Huang, and T. J. Liu, ''A Simple Model for Heat Transfer inside an Extrusion Die,'' *Poly. Eng. Sci.*, **35**, 1714 (1995).

Yu, W. J., T. A. Yu, and T. J. Liu, ''Reduction of Minimum Wet Thickness in Extrusion Slot Coating,'' *Chem. Eng. Sci.*, **50**, 917 (1995).

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