A STUDY OF THE APERTURE FILLING PROCESS IN SOLDER PASTE STENCIL PRINTING

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ABSTRACT

Stencil printing has been the dominant method of solder deposition in surface mount assembly. With the development of advanced packaging technologies such as ball grid array (BGA) and flip chip on board (FCOB), stencil printing will continue to play an important role. However, the stencil printing process is not completely understood because 52 - 71 percent of fine and ultra-fine pitch surface mount assembly defects are printing process related (Clouthier, 1999). This paper proposes an analytical model of the solder paste deposition process during stencil printing. The model derives the relationship between the transfer ratio and the area ratio. The area ratio is recommended as a main indicator for determining the maximum stencil thickness. This model explains two experimental phenomena. One is that increasing stencil thickness does not necessarily lead to thicker deposits. The other is that perpendicular apertures print thicker than parallel apertures.

1 INTRODUCTION

The requirements of smaller size, lighter weight and higher performance for printed circuit boards (PCB) led to the trend of electronic packaging and interconnection away from through-hole technology and towards surface mount technology (SMT). With a growing need for denser packaging and a drive for higher pin count, SMT has evolved from standard SMT (pitches of larger than 1 mm) to fine pitch SMT (pitches of between 0.5 mm to 1 mm) and ultra fine pitch SMT (pitches of less than 0.5 mm).

Since it was first used at IBM Austin in 1983, stencil printing has been widely used and has been the dominant method of solder deposition in production volume surface mount assembly. With the development of advanced packaging technologies such as ball grid array (BGA) and flip chip on board (FCOB), stencil printing will continue to play an important role. However, it was reported that 52 - 71 percent of fine and ultra-fine pitch surface mount assembly defects are solder paste stencil printing process related (Clouthier, 1999). In order to fully take advantage of the SMT benefits and improve the product performance and quality, understanding and optimizing the stencil printing process are necessary.

The stencil printing process can be divided into three stages: the paste travel stage (Stage I), the aperture filling stage (Stage II), and the paste release stage (Stage III). In stage I, the squeegee forces the paste roll in front of the squeegee and generates a high pressure. In stage II, the high pressure injects the paste into the stencil aperture. In stage III, the stencil releases and paste is left on the pad of the PCB. A schematic of the stencil printing process is shown in Figure 1.

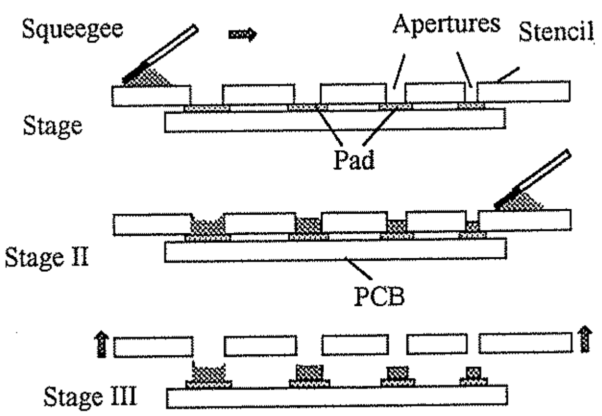


Fig. 1 Schematic diagram of the stencil printing process

There are many variables that affect the stencil printing process. The components of the stencil printing process include the printer, the substrate, the stencil, the squeegee, the solder paste, and the process parameters. Since there are many independent variables, an analysis is necessary to determine the critical input variables that affect the output variables. Here the output variables are the volume and its deviation of deposited solder paste, the area and its deviation of solder paste deposited, the thickness and its deviation of solder paste deposited, and the position of solder paste deposited relative to the pad of the PCB. Control of the correct volume of paste on the board is essential in order to avoid solder bridges (too much solder paste), and open solder joints (insufficient solder paste). If applied to BGA and FCOB, the thickness control is also important to attain low defect levels. Because of the complexity of the printing process, constantly changing component technology and new solder paste introduction, and difficulty of measuring some process variables such as solder paste viscosity (non-Newtonian) and deformed squeegee angle, the stencil printing process is still considered by many to be a black art.

Many experimental investigations of the relationships between the input variables and the output variables have been carried out. The huge empirical database, as a result of experiments, has played an important role in guiding the industry to implement the stencil printing process. As a result of the studies, two experimental phenomena have been difficult to understand. One is that increasing stencil thickness does not increase the thickness of paste deposited (Fujiuchi and Toriyama, 1994; Whitmore, et al., 1997). The other is perpendicular apertures (longer side of the apertures perpendicular to the squeegee travel direction) print thicker paste deposits than parallel apertures (Mannan, et al., 1994; Markstein, 1997).

This paper proposes an analytical model of the stencil printing process that reveals the solder paste deposition mechanism and therefore explains the above experimental phenomena. The maximum stencil thickness and the critical variables that control the print quality will be derived from the model. The model is expected to help industry to improve yield, reduce defects, reduce rework, and enhance time-to-market.

2 NOMENCLATURE

ARR	Area ratio
ASR	Aspect ratio
D	Distance of the paste extending from the tip of the squeegee in the direction of travel
H	Thickness of the stencil
L	Length of the rectangular aperture or the slit
P	Paste pressure
R	Radius of the circular aperture
S	Squeegee speed
T	the total filling time
TR	Transfer ratio
U	Squeegee speed
V	Total deposited volume
W	Width of the rectangular aperture or the slit
r	Distance from contact point between squeegee and screen, also used for position vector in cylindrical coordinates.
t	the instantaneous filling time
v	Paste velocity (vector)
α	Squeegee actual attack angle
η	Paste viscosity
ρ	Density of the paste
∇	Gradient operator
∇^2	Laplacian operator
ψ	Stream function
f(Q)	Paste quantity factor

3 REVIEW OF RELATED WORK

3.1 Effects of the Stencil

The stencil is a thin foil with small apertures. Brass, stainless steel, alloy 42, and molybdenum are typical materials used for stencil foil. Stencils are commonly manufactured by chem-etch and laser cut processes.

Ideally, the length (L) and width (W) of the aperture and the thickness (T) of the stencil determine the volume of the solder paste deposited, and the thickness of the stencil determines the thickness of the solder deposited. However, this is not always true. Fujiuchi and Toriyama (1994) reported that the bump volume with a stencil thickness of 60 μm is larger than that of a stencil thickness of 80 μm. Whitmore, et al. (1997) found that increasing stencil thickness does not necessarily lead to thicker deposits. So the question is how to determine the maximum stencil thickness for different aperture sizes. Aspect ratio and area ratio are recommended as important stencil design guides in determining the maximum stencil foil thickness in industry. The aspect ratio is defined as the width of the aperture divided by the height of the aperture (or the thickness of the stencil). The area ratio is the ratio of the area of aperture opening to the area of the sidewall of the aperture. But different recommendations have been published. For example, Wilson and Bloomfield (1995) suggested the optimal aspect ratio of 1.25. Coleman (1996) recommended larger than 1.5 for the aspect ratio and larger than .66 for the area ratio. Markstein (1997) proposed the generally accepted aspect ratio is larger than 1.5 (1.8 for chemically etched stencils and 1.2 for electropolished laser-cut and electroformed stencils).

Empirical observations show that perpendicular apertures print higher than parallel apertures. Markstein (1997) reported accurately that deposited paste thickness was about 6% greater when the aperture length was oriented parallel to the squeegee blade than when apertures were oriented perpendicular to the squeegee. However, interior angle or polygon geometry had no effect on paste deposition, and aperture sidewall taper had a noticeable difference in print quality when near-square sidewalls were used (Monghan, et al. 1995).

3.2 Effects of the Solder Paste

The solder paste may play a critical role in determining stencil print quality. Generally, solder paste with fine particles, high viscosity, high yield point, high thixotropy and minimal slump tend to perform well (Morris and Wojcik, 1991).

Paste rheology is a very important variable to predict the printing behavior of the solder paste. Good rheology solder paste has the tendency to flow when stressed by the squeegee and the tendency to keep the printed columns from slumping once the stencil is lifted. Viscosity and thixotropic properties are the two most important parameters of paste rheology.

Solder paste particle size, metal load, and flux/vehicle rheology are the main elements to affect the paste rheology.

A solder paste is specified by the maximum and minimum ball sizes comprising the paste. The typical designation like -325/+500 means that the solder alloy particles pass through a 325 mesh screen but cannot pass through a 500 mesh screen (or refers to the diameter of solder particle size between 0.0254mm and 0.0432mm). For details see ASTM B-214, *Test for Sieve Analysis of Granular Metal Powers.* Hwang (1989a) recommended the diameter of the largest particle should be less than one-third the smallest dimension of the stencil. Xiao, et al. (1993) suggested that the maximum powder size allowed is approximately 1/7 of the typical aperture width. Although a fine powder is required for good printability, too fine powder is a detriment to the rheological property. The reason is that too many small particles have too large a surface area, which demands more flux than usual to remove all the oxides present on the particle's surface (Danielsson, 1995).

Metal load is not only an important variable to influence the paste rheology but also a critical variable in determining the deposited volume and thickness after reflow. The metal load is defined as the percentage of solder paste solids content. A metal load of 90.5 to 91% seems to be the optimum for most properties (Xiao, et al. 1993). The vehicle of the solder paste is primarily a carrier for the solder paste and provides the desirable rheology essential for printing. The function of fluxes is to clean the surfaces to be joined, to clean the surface of the solder powder, and to maintain the cleanliness during reflow. Common flux types include rosin (R), rosin mildly active (RMA), rosin active (RA), synthetic activated (SA), and other additives (OA) (Hwang, 1989b).

3.3 Effects of the Process Variables

Squeegee pressure: Proper squeegee pressure should be set enough for a clean wipe of the stencil. Too much pressure on the squeegee will cause the prints to smear and may damage the stencil, while too little squeegee pressure will cause the solder to skip and provide insufficient wetting (Lau, 1994).

Squeegee hardness: A metal squeegee is commonly used in stencil printing because it provides more consistent paste prints than a polyurethane squeegee. However a polyurethane squeegee has advantages in a step-stencil printing. The durometer of a polyurethane squeegee is the measure of its hardness, which means the ability of the blade to resist bending during printing. Durometer is measured on the Shore A scale. The higher the durometer, the greater the blade rigidity. Generally, a hardness of 60 to 85 is suitable for screen printing, and a hardness of 80 to 100 is good for stencil printing.

Squeegee angle: A squeegee angle of 45° is most commonly used in industry. Lideen and Dahl (1994) reported that the 129 durometer squeegee at 45°, the composite squeegee at 45°, and the metal squeegee at 60° have proven to be the best squeegees for both ultra fine pitch and other larger pitch printing because these squeegees gave the most consistent print and the volume of the print was closest to the designed volume.

Print speed: There is conflicting experimental results concerning print speed. Mannan, et al. (1994) found a linear rise in paste height with squeegee velocity during stencil printing. Wilson and Bloomfield (1995) reported that no noticeable deterioration in print height occurred in print speeds from 25 mm per second to approaching 200 mm per second. Lau (1994) noted that the squeegee speed depends on the viscosity of the paste.

Snap-off distance: The snap-off distance is the distance between the bottom of the stencil and the substrate. Usually, stencil printing is on-contact, which means the snap-off distance is zero. Wilson and Bloomfield (1995) found that a small snap-off distance helps paste release from ultra fine pitch apertures.

Separation speed: Different opinions exist in explaining the separation speed function. Whitmore et al. (1997) suggested that the separation speed is critical for paste release. However, Ekere, et al. (1993) studied the stencil/substrate separation speed based on experiments, and concluded that the speed of separation does not significantly affect the number of printing defects for some solders whereas for others a very low value of separation speed results in more defects. Sahay, et al. (1995) presented an analytical model for the release process that implies the separation speed is not an important parameter for print quality.

4 MODELING OF THE DEPOSITION PROCESS

Solder paste can be considered as a kind of fluid, so it cannot be represented by a single concentrated mass location at a fixed center of gravity. In this study, the following assumptions are made:

- The solder paste is a Newtonian fluid. This assumption is questionable because solder paste exhibits pseudoplasticity (or shear-thinning) and thixotropy. However, modeling the solder paste as a non-Newtonian fluid is difficult. There is no simple way to do this since the rheological behaviors of the solder paste depend on their composition and manufacturer. Not only different solder paste types have different rheological properties but also some similar solder types made by different manufacturers also have different rheologies. Detailed discussions refer to Hwang (1989b) and Ekere and Lo (1991).
- The flow is incompressible.
- There is no leakage under the squeegee.
- This is a two dimensional problem.
- The inertia term is negligible in the momentum equation. This assumption is reasonable because the viscosity of solder paste is very high (about 1000 kcps) so that its Reynolds number is very low ($< 10^{-5}$). For so small of a

Reynolds number, Stokes' creeping-flow theory can be used effectively.

- The paste does not slip on the stencil surface. It should be noted that the no-slip condition is assumed only at the stencil surface with respect to the paste travel stage (stage I). Slip at the aperture wall at the stencil release stage (stage III) is well-documented phenomenon (Mannan, et al., 1995).

4.1 The Hydrodynamics of Paste Travel Process

Based on above approximations, the Stokes' equation for creeping-flow is

$$\nabla P = \eta \nabla^2 \mathbf{v} \tag{1}$$

As shown in Figure 2, solder paste is bounded by the squeegee and the stencil. The squeegee and the stencil meet at an angle α, which is squeegee angle. The squeegee moves at a velocity U and the stencil is at rest.

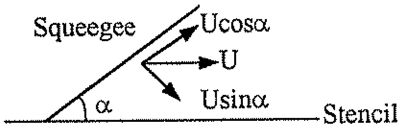


Fig. 2 Flow between the squeegee and the stencil

The problem will be easiest to solve in the cylindrical coordinates system. The stream function, $\psi(r, \theta)$, for a planar flow in cylindrical coordinates is defined as (Deen, 1998)

$$v_r = (1/r)\partial\psi/\partial\theta \qquad v_\theta = -\partial\psi/\partial r \tag{2a,b}$$

The stream function form of Stokes' equation is

$$\nabla^4\psi = 0 \tag{3}$$

$$\nabla^4 = \nabla^2(\nabla^2) \qquad \nabla^2 = (1/r)\partial(r\partial/\partial r)/\partial r + (1/r^2)\partial^2/\partial\theta^2$$

The no-slip and no-penetration conditions at the squeegee ($\theta=\alpha$) and the stencil ($\theta=0$) are expressed as

$$v_r(r, \alpha) = U\cos\alpha \qquad v_\theta(r, \alpha) = -U\sin\alpha \tag{4}$$

$$v_r(r, 0) = 0 \qquad v_\theta(r, 0) = 0 \tag{5}$$

Using Eq. (2a,b), these boundary conditions are written in terms of ψ as

$$\partial\psi/\partial\theta\,(r, \alpha) = Ur\cos\alpha \qquad \partial\psi/\partial r\,(r, \alpha) = U\sin\alpha \tag{6}$$

$$\partial\psi/\partial\theta\,(r, 0) = 0 \qquad \partial\psi/\partial r\,(r, 0) = 0 \tag{7}$$

Examining the boundary conditions in Eq. (6), it appears the solution may be of the form

$$\psi = rf(\theta) \tag{8}$$

Substituting Eq. (8) in Eq. (3),

$$d^4f/d\theta^4 + 2\, d^4f/d\theta^4 + f = 0 \tag{9}$$

The general solution for Eq. (9) is

$$f(\theta) = A\cos\theta + B\sin\theta + C\theta\cos\theta + D\theta\sin\theta \tag{10}$$

where A, B, C, and D are constants.

Using these boundary conditions to evaluate the constants in Eq. (10), we obtain

$$A = 0$$

$$B = -C = U\sin^2\alpha/(\sin^2\alpha - \alpha^2)$$

$$D = U(\sin\alpha\cos\alpha - \alpha)/(\sin^2\alpha - \alpha^2)$$

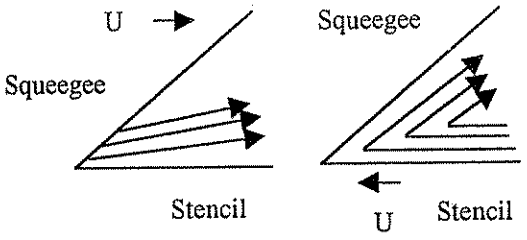
The stream function is found to be

$$\psi(r, \theta) = Ur[\sin^2\alpha\sin\theta - (\sin^2\alpha)\theta\cos\theta + (\sin\alpha\cos\alpha - \alpha)\theta\sin\theta]/(\sin^2\alpha - \alpha^2) \tag{11}$$

Riemer's (1988a,b) result was

$$\psi(r, \theta) = Ur[\alpha^2\sin\theta - (\sin^2\alpha)\theta\cos\theta + (\sin\alpha\cos\alpha - \alpha)\theta\sin\theta]/(\sin^2\alpha - \alpha^2) \tag{12}$$

as a result of modeling the squeegee as fixed and the screen moving toward the squeegee with a velocity U.



(a) (b)

Fig. 3 Streamline (a: the model; b: Riemer's model)

Since most stencil printing and screen printing involves a stencil or screen at rest and a squeegee moving, the model developed here more accurately represent the stencil printing process. The velocity components are

$$v_r = U[\sin^2\alpha\cos\theta - \sin^2\alpha(\cos\theta - \theta\sin\theta) + (\sin\alpha\cos\alpha - \alpha)(\sin\theta + \theta\cos\theta]/(\sin^2\alpha - \alpha^2) \tag{13a}$$

$$v_\theta = -U[\sin^2\alpha\sin\theta - \sin^2\alpha\,\theta\cos\theta + (\sin\alpha\cos\alpha - \alpha)\theta\sin\theta]/(\sin^2\alpha - \alpha^2) \tag{13b}$$

The r component in Eq. (1) is

$$\partial P/\partial r = 2(\eta U/r^2)[\sin^2\alpha\cos\theta - (\sin\alpha\cos\alpha - \alpha)\sin\theta]/(\sin^2\alpha - \alpha^2)$$

At the stencil surface ($\theta = 0$),

$$\partial P/\partial r|_{(\theta=0)} = 2(\eta U/r^2)\sin^2\alpha/(\sin^2\alpha - \alpha^2) \tag{14}$$

The pressure P at the stencil surface is

$$P = \int_0^r \partial P/\partial r|_{(\theta=0)}\, dr = 2(\eta U/r)\sin^2\alpha/(\alpha^2 - \sin^2\alpha) \tag{15}$$

The shear rate in the solder paste at the stencil surface is

$$\tau_{\theta r}|_{(\theta=0)} = (2\eta U/r)(\sin\alpha\cos\alpha - \alpha)/(\sin^2\alpha - \alpha^2) \tag{16}$$

where r = Distance from the contact point between squeegee and stencil.

The obtained shear rate and pressure in the solder paste at the stencil surface agree with the results of Riemer (1988a, b). Eqs. (15) and (16) show that the shear rate and pressure of the solder paste at the stencil surface are proportional to the squeegee speed and paste viscosity, inversely proportional to distance to the vicinity of the squeegee, and a function of the squeegee angle. Since solder paste is a pseudoplastic (shear-thinning) fluid, the viscosity decreases with an increase of shear rate. This characteristic is desirable in the stencil printing process. Therefore, high shear rate is required during the aperture filling process. Table 1 compares the pressure and the shear stress at the stencil surface with different squeegee angles.

Table 1. Pressure and Shear Stress vs. Squeegee Angle

Squeegee Angle	Pressure at the stencil surface	Stress at the stencil surface
60°	$4.33\eta U/r$	$3.54\eta U/r$
45°	$8.55\eta U/r$	$4.88\eta U/r$
30°	$20.7\eta U/r$	$7.5\eta U/r$

4.2 The Aperture Filling Process

It should be noted that the aperture filling process could not be modeled as a Poiseuille flow, which assumes capillary tubes of infinite length. In the stencil printing process, the stencil is only a thin foil.

Roscoe (1949) studied the high viscous fluid flow through an aperture in a thin plate. He obtained the relationship between the rate of flow per unit time Q and pressure difference between the two sides. His results are

Flow through a circular aperture: $Q = PR^3/(3\eta)$ (17)

Flow through a slit (L>>W): $Q = \pi PLW^2/(32\eta)$ (18)

Considering the symmetry of a rectangle aperture, flow rate Q through a rectangle aperture should be

$$Q = \pi PL^2W^2/(32\eta(L+W)) \quad (19)$$

Substituting Eq. (15) in Eqs. (17), (18), and (19) yields

Circular aperture: $Q = 0.67\ (UR^3/r)f(\alpha)$ (20)

Slit: $Q = 0.2\ [ULW^2/r]\ f(\alpha)$ (21)

Rectangle aperture: $Q = 0.2\ [UL^2W^2/((L+W)r)]\ f(\alpha)$ (22)

Where $f(\alpha) = \sin^2\alpha/(\alpha^2 - \sin^2\alpha)$

Total deposited volume (V) is

$$V = \int_0^T Q dt = \int_0^D Q/U dr \quad (23)$$

Where

T = the total filling time = D/U

t = the instantaneous filling time = r/U

By substituting Eqs. (20), (21), and (22) into Eq. (23), the total volume is determined to be:

through a circular aperture: $V = 0.67\ R^3\ f(\alpha)f(Q)$ (24)

through a slit:

$$V = 0.2\ [LW^2]\ f(\alpha)f(Q) \quad (25)$$

through a rectangular aperture:

$$V = 0.2\ [L^2W^2/(L+W)]\ f(\alpha)f(Q) \quad (26)$$

where

$$f(Q) = \int_0^D (1/r)dr$$

f(Q) is a paste quantity factor that increases with paste quantity in front of the squeegee. Equation (8) shows that f(Q) will be infinite when $r \to 0$, which indicates that the paste pressure in Equation (4) increases to an extremely high value in the vicinity of the squeegee edge. However, in an actual printing situation, paste pressure is limited by the capability of the paste to transfer shear stresses at high shear rates, and also by the quality of the seal between the squeegee and the stencil. In order to generate the high pressure to inject the paste into the aperture, stencil planarity, PCB board planarity, and squeegee parallelism must be precisely controlled.

Equations (24) and (25) show that the deposited volume is independent of the thickness of the stencil. It relates to the actual attack angle and aperture size. It should be noted that this holds true as long as the deposited volume is less than the aperture volume. If the deposited volume is larger than the aperture volume, the squeegee will scoop the excess paste. In the actual situation, the volume of paste deposited when a thicker stencil is used may be less than the volume of paste deposited when a thinner stencil is used because more paste may stick to the wall of the thicker stencil.

4.3 Paste Transfer Ratio vs. Aspect Ratio

As defined in Section 3, the area ratio (AAR) is:

For a circular aperture: $ARR = \pi R^2/(2\pi RH) = R/(2H)$ (27)

For a rectangle aperture: $ARR = LW/[2(L+W)H]$ (28)

The aspect ratio (ASR) is

$$ASR = W/H \quad (29)$$

Define transfer ratio (TR) as the deposition volume divided by the aperture volume. Substituting Eqs. (24), (25), and (26) as the deposited volume yields

For the circular aperture: $TR = 0.42\ f(\alpha)f(Q)ARR$ (30)

For the rectangle aperture: $TR = 0.4\ f(\alpha)f(Q)ARR$ (31)

For the slit: $TR = 0.2\ f(\theta)f(Q)ASR$ (32)

Equations (30) and (31) show that the transfer ratio is proportional to the area ratio. But the conclusion that the transfer ratio is proportional to the aspect ratio can be drawn only if the length L of a rectangle aperture is much larger than its width W (L>>W). In addition, it is difficult to determine the width of a circular aperture in Eq. (29). Therefore, the area ratio is recommended as an indicator for choosing the stencil thickness. This is consistent with Coleman's (1996) experience.

f(Q) is mainly determined by the seal condition between the squeegee and the stencil. If the squeegee angle is fixed and f(Q) is assumed to be constant (unknown), the relationship between the transfer ratio and the area ratio will be:

$TR = C * AAR$ $\quad AAR <$ a critical value

$TR = 1$ $\quad AAR >$ a critical value

Where C is a constant.

The critical point is where the deposited solder paste volume equals the aperture volume and no excess paste is scooped. According to industry experience and our experiment, the critical point is between 0.6 to 0.7. The maximum stencil thickness can be determined by the critical value.

For a circular aperture: $H_{max} < 0.7\sim0.8\ R$

For a rectangle aperture: $H_{max} < 0.7\sim0.8\ LW/(L+W)$

4.4 Printing Perpendicular vs. Parallel Aperture

As mentioned previously, a perpendicular aperture prints higher than a parallel aperture. Two possible explanations exist. One is less paste is scooped in a perpendicular aperture than a parallel one. The other is the difference in pressure that occurs under the squeegee in the two kinds of apertures. Mannan, et al. (1994) analyzed the static deformation and dynamic deformation of the squeegee and concluded that a perpendicular aperture will be scooped more than a parallel aperture. Then they deduced that the differences in paste height are due to the different pressures underneath the squeegee in the two cases.

The pressure difference between a perpendicular aperture and a parallel aperture can be explained as follows. From the analysis in Section 4.2, the paste deposited volume is proportional to the paste pressure and the highest pressure of paste occurs in the vicinity of the squeegee edge. It should be noted that these conclusions are derived based on the assumption that there is no paste leakage under the squeegee, i.e. the paste speed at the contact point is zero. However, when the squeegee is over the aperture, there is normal velocity of paste through the aperture under the squeegee as shown in Figure 4. In this case the normal velocity is constant because of no inertia term. Since the normal velocity occurs, the paste pressure above the aperture would drastically decrease. In other words, the highest paste pressure occurs at the edge of the aperture or when the squeegee just reaches the aperture. A perpendicular aperture has a longer side than a parallel aperture at that time. This is why a perpendicular aperture prints higher.

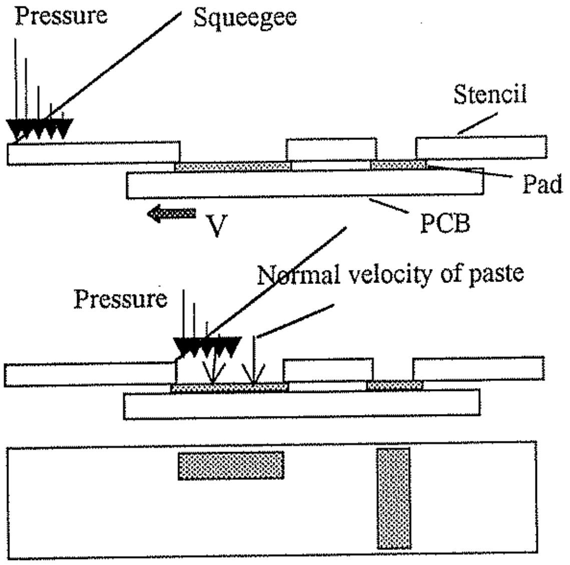


Fig. 4 Aperture filling mechanism

5. EXPERIMENTAL VALIDATION

An experiment was conducted to validate the model. Two stencils with thicknesses of 0.1 mm (4 mil) and 0.15 mm (6 mil) were selected. The test pattern featured circular apertures and rectangular apertures of 5 different pitches ranging from 0.76 mm (30 mil) to 0.3 mm (12 mil). The volume of deposited solder paste was measured by an in-line fully automatic laser-based 3-D triangulation solder paste inspection system. The area ratios and the transfer ratios were calculated. The detailed experimental design and data analysis is discussed by Pan, et al. (1999). The comparison of the theoretical model and experimental data is shown in Fig. 5. The difference between the model and experimental results can be explained because part of the paste was deposited off the pad due to the alignment between the stencil and PCB. Another reason is that some paste sticks on the sidewall of the aperture when AAR < 0.6 but no paste sticks when AAR > 0.6. Both phenomena have been observed during the experiment. Overall, the experimental results strongly support the model.

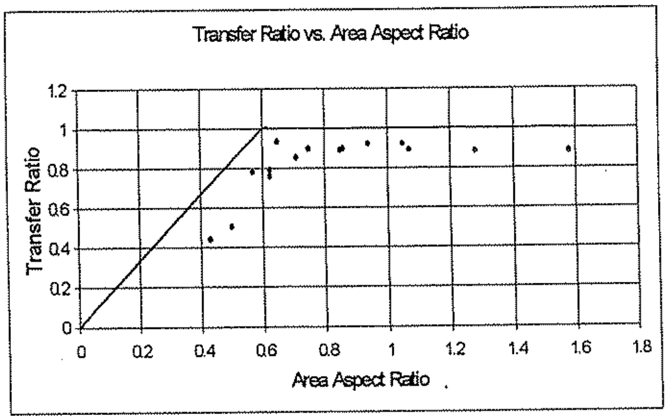


Fig. 5 Comparison of the model and experimental results (points: experimental data; line: model)

6. SUMMARY AND CONCLUSIONS

An analytical model has been developed for the deposition process of the stencil printing. The following conclusions are made:

1) Aperture opening size and paste pressure generated determine the amount of solder paste deposited. The volume of paste deposited is independent of the stencil thickness when the deposited volume is less than the aperture volume. Area ratio is recommended as a main indicator for determining the thickness of a stencil.
2) The α in Equations (9) and (10) is the actual attack angle. It is determined by the squeegee angle, the squeegee pressure, and the squeegee hardness. The smaller the α, the more paste that is deposited.
   - From the model, the squeegee angle should have a significant effect in adjusting the volume of deposited paste. However, most squeegee holders used in industry do not have the ability to adjust the angle.
   - The higher the squeegee pressure (smaller α), the more paste is deposited. But too high a squeegee pressure will cause stencil deformation, which leads to paste leakage under the squeegee and different pressures along the squeegee blade. So too high a squeegee pressure would lead to unsatisfactory print

quality. In addition the high squeegee pressure would destroy the stencil or decrease the stencil life. Proper squeegee pressure should be set high enough for a clean wipe of the stencil.

  - The higher the squeegee hardness, the more robust the paste deposits because of its keeping α constant. This is why industry generally chooses a metal squeegee for solder paste printing.

3) A perpendicular aperture prints higher than a parallel aperture. One way to avoid the difference between a perpendicular aperture and a parallel aperture may be to design 45 degrees and 135 degrees apertures with respect to the squeegee, or design the parallel aperture slightly bigger relative to the perpendicular aperture.
4) Stencil planarity, PCB board planarity, and squeegee parallelism are required to generate the high pressure to inject the paste into the aperture.

ACKNOWLEDGMENTS

The authors wish to thank Visteon Automotive Systems for the use of equipment in conducting the experiments.

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