A Study of Solder Paste Flow inside a Sealed Printing Head

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Abstract

In the assembly of Printed Circuit Boards (PCBs) using Surface Mount Technology (SMT), solder paste is deposited on the bond pads of the PCBs using stencil/screen printing technique. The last few years have seen the development and introduction of new printing mechanism to meet the miniaturisation challenge of electronic products. The most notable is the development of new printing heads such as the ProFlow [1, 2] and the Rheometric Pumping Head [3]. Unlike the traditional squeegee blade, in these new printing devices the solder paste is contained in a sealed pressurised chamber, and is released during the printing stroke via an opening as the printing head passes over the stencil apertures. The flow profile of the solder paste inside such a chamber plays a key role in determining the volume of solder paste deposited onto the PCB pads. In this paper we investigate the paste flow inside such a chamber and its influence on the aperture filling. Our results show that the paste does not vertically fill the apertures, but has a horizontal velocity component in the printing direction. This horizontal velocity component will lead to insufficient filling of paste at the rear corner of the aperture. To counteract the influence of this undesirable velocity component, we propose to introduce a horizontal shaft perpendicular to the printing direction inside the chamber. During a printing stroke this shaft rotates inside the chamber in the printing direction and drives the paste near the bottom slot to flow against the printing direction. We present an analysis of the paste flow inside such a device and the nature of the aperture filling process. The main parameters that influence the paste flow are the diameter, the rotational speed and the position of the shaft. The key to obtaining sufficient and consistent paste deposits is to minimise the horizontal velocity component of the paste to ensure the paste fills into the aperture vertically, and to maximise the vertical velocity component of the paste to shorten the aperture filling time. The introduction of such a shaft is also expected to significantly reduce the pressure loading on the paste at the top of the chamber.

Introduction

As the electronics market moves towards higher performance PCBs, the number of inputs and outputs on a unit area of the PCBs continues to increase. This results in a strong need for the electronics manufacturing industry to develop new and low cost PCB assembly techniques. Electronics manufacturing industry also faces the high pressure to control environmental pollution induced from its production activities.

Solder pastes are still widely used as the main electrical and mechanical connecting material between components and PCBs. In PCB assembly using SMT, solder paste is deposited on the bond pads of PCBs and area array packages, such as Ball Grid Arrays (BGAs), and Chip Scale Packages (CSPs), by stencil/screen printing technique. Getting high resolution and consistent volumes of deposits of solder paste on PCBs is one of the key steps in SMT assembly process to ensure robust connections between components and PCBs.

Stencil/screen printing of solder paste using a traditional squeegee blade is a mature technique which has been used in SMT for more than three decades. This technique is suitable for low cost continuous assembly and high throughput. However, as the density of inputs and outputs of PCB continues to increase, the limitations of this technique such as the exposure of the solder paste to the working environment, means that it is unable to print consistently at very fine pitch sizes.

To overcome the shortcomings of the squeegee blade printing system, new printing techniques are demanded. The sealed printing devices, such as the ProFlow [1, 2], and the Rheometric Pumping Head [3], have been developed in the last couple of years. As a new technique, the working principle of such devices has not been fully understood yet although initial experimental and CFD studies have been done. In this paper we employ the CFD results obtained by other investigators to analyse the influence of the velocity profile of solder paste inside the sealed printing head on the aperture filling process. From the analysis, we predict that the potential disadvantage of the new devices is insufficient aperture filling. We demonstrate that the main reason is that the paste does not vertically fill the apertures but with horizontal velocity component in the printing direction. To offset the influence of this undesirable horizontal velocity component we put forward a proposal to improve the aperture filling process. The main idea of this proposal is to delete the horizontal velocity component by a rotational shaft inside the printing head to ensure that the paste vertically fills the apertures. To benefit from the knowledge of the printing process using squeegee blade, we briefly review this printing technique first.

Review of Stencil Printing Process Using Squeegee Blade

The stencil/screen printing of solder paste using squeegee blade for SMT has been well studied by many investigators [4-8]. As shown in Figure 1, during a printing stroke, the squeegee blade pushes the solder paste to roll on the stencil surface. As the blade passes over an aperture the paste is squeezed to fill it. At the end of the printing stroke, the blade is lifted first; then the stencil is separated from the PCB and the paste is deposited on the bond pads. Investigations showed that, the printing process is controlled by the complicated interactions of many variables. These variables are the rheology of the solder paste, the material and the hardness of the squeegee blade, the stencil surface finishing, the method of the aperture formation, the stencil and squeegee contacting force and the mounting angle α of the squeegee *etc*. One of the keys to obtain full aperture filling is that the solder paste must roll on the stencil without slip, thus building up high-pressure near the squeegee blade tip. The complete rolling of paste ensures that it vertically fills the aperture. Due to the deformation of the blade, it may dig into the aperture, which leads low deposit height. This low deposit height can be compensated by the backward flow of paste beneath the blade tip caused by the high-pressure (see Figure 1). To obtain such an effect, the mounting angle of the squeegee blade is the most important factor. Experimental and analytical studies showed that the suitable range of α is from 50^o to 75^o depending on the rheology of the paste. If α is smaller than 50^o excessive high-pressure tends to lift the blade from the stencil. Whereas if α is greater than 75^o the paste may slip on the stencil and the pressure near the blade tip will not be high enough to squeegee the paste into the aperture, thus leading to insufficient aperture filling. Figure 1 also compares the profiles of good deposit with bad deposit on PCBs due to the paste slip in printing. The bad deposit can lead to connection defect.

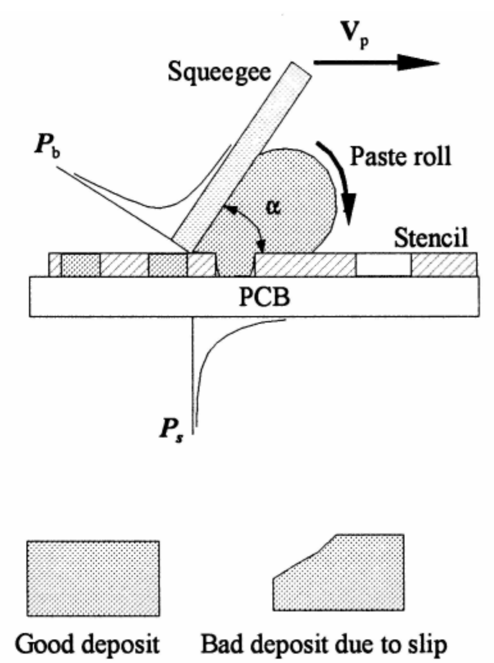

Figure 1. Stencil printing of paste using squeegee blade and imperfect deposit profile due to paste slip in printing.

Due to the full exposure of solder paste to the working environment, the use of the squeegee blade may suffer from its inherent shortcomings. First, it can cause environmental pollution due to the evaporation of the flux/vehicle system of the solder paste. Second, this evaporation can also change the rheological properties of the solder paste. To obtain consistent volumes of deposits, the rheological properties of solder paste must be maintained the same throughout a working day. Such a requirement becomes even more important as the volumes of the deposits are continuously decreasing. Finally, solder paste left on the stencil after a working day can not be reused in the following day due to the change of rheology, thus, increasing the production cost.

Analysis of the Performance of Sealed Printing Heads

The sealed printing heads, such as the ProFlow [1, 2] and the Rheometric Pumping Head [3], have been developed in the last couple of years to overcome the shortcomings of the squeegee blade. Figure 2 shows a sketch of the printing head. The significant difference of the new devices from the squeegee blade is that the solder paste is sealed inside a chamber. Pressure P is loaded on the paste from the top of the chamber. At the bottom there is a narrow slot. During a printing stroke, the frictional force between the stencil and the paste at the slot drives the paste to flow inside the chamber. As the printing head passes over the aperture, the paste flows out the slot and fills the aperture. The use of such printing heads can reduce the risk of environmental pollution. It also avoids the evaporation of flux/vehicles from the solder paste, thus maintaining consistent rheological properties of the solder paste for a long period and obtaining high printing quality. Paste left inside the chamber after one working day can also be used in the following days which reduces the production cost.

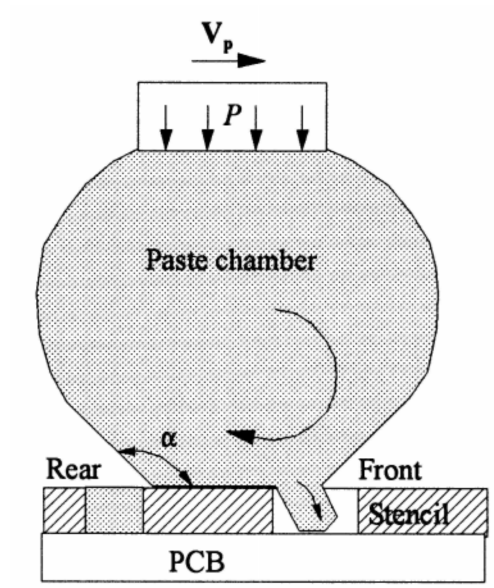

Figure 2. Stencil printing of paste using sealed head.

Experimental and CFD analytical studies [1-3] have been carried out on the sealed printing heads. These initial studies provide useful information for an insight of the performance of such devices. However, as a new technique, the working principle has not been fully understood yet. The CFD results have not correlated the paste flow inside the chamber to the aperture filling process. In the following, we analyse the aperture filling process using CFD results and the knowledge of squeegee blade printing.

Figure 3 shows a typical velocity profile of solder paste inside the chamber [3] in which no slipping boundary condition is applied between the paste and the stencil at the slot. It is seen that the paste rotates insider the chamber and the rotational centre is near the slot. Similar to the use of squeegee blade, the paste velocity near the slot is the main factor affecting the aperture filling. So we concentrate on examining the paste flow near the front side of the slot as shown in Figure 4. Notice that in Figure 3 the paste velocity is relative to the moving printing head. Therefore, the absolute velocity $\mathbf{V_a}$ (relative to the static stencil) of the paste can be written as:

$$\mathbf{V_a} = \mathbf{V_p} + \mathbf{V_r} \qquad (1)$$

Where $\mathbf{V_p}$ is the velocity of the printing head (the printing speed) and $\mathbf{V_r}$ is paste velocity relative to the printing head. $\mathbf{V_p}$ can be decomposed into horizontal and vertical components as:

$$\mathbf{V_a} = \mathbf{V_x} + \mathbf{V_y} \qquad (2)$$

When the front side of the chamber arrives at the rear edge of the aperture the paste starts to fill it with velocity $\mathbf{V_a}$. During the aperture filling, both the absolute value and the direction of $\mathbf{V_a}$ may vary due to the gravity and the pressure *P*. Figure 4 shows the different stages of aperture filling. We can see that, the existence of $\mathbf{V_x}$ is undesirable. It prevents the paste filling the rear bottom corner of the aperture and the higher the $\mathbf{V_x}$ the larger the empty volume. While, high value of $\mathbf{V_y}$ can promote aperture filling.

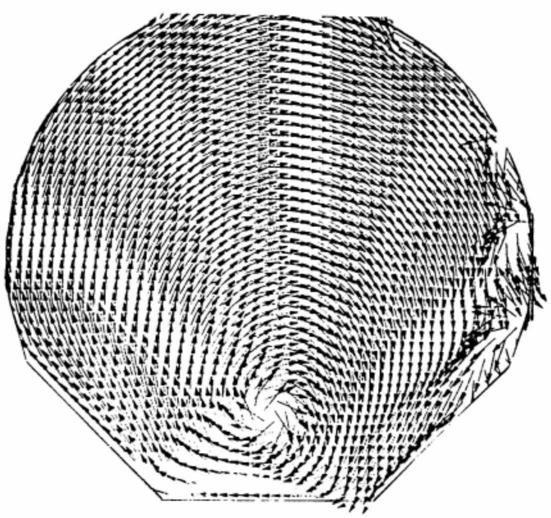

Figure 3. CFD result of paste velocity profile inside the printing head.

The above analysis is based on the CFD results in which both no slipping boundary condition and Newtonian fluid were assumed and the pressure *P* was not taken into consideration [2]. As concentrated suspensions, these assumptions may not accurately describe the physical properties of solder paste and the printing process. Ignoring the pressure *P* makes it impossible to investigate its influence on the aperture filling. To take all these factors into consideration, the paste flow inside the chamber can be analysed as follows.

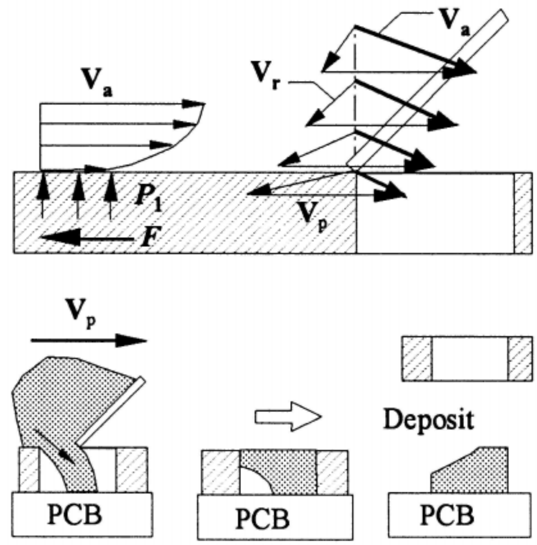

Figure 4. The frictional force of the stencil on the paste and paste velocity in aperture filling.

The paste flow inside the chamber is merely driven by the frictional force *F* between the stencil surface and the paste at the slot. This frictional force is the sum of the lubricating forces between the stencil and the nearest solder particles to it. Taking an element of paste contacting the stencil at the slot, as shown in Figure 4, the frictional force *F* on the paste on a unit area can be written in different forms as:

$$F = -\mu_p \frac{dV_x}{dy} = -\frac{16}{5}\pi\mu_f \sum_{i=1}^{n} d_i V_{xi} \ln\frac{d_i}{\delta_i} = \alpha P_1 \qquad (3)$$

Where $dV_x/dy = \dot{\gamma}$ is the shear rate in the paste at the stencil surface, μ_p is the viscosity of solder paste, μ_f is the viscosity of the flux/vehicle system in the solder paste, n is the number of the nearest particles to the stencil, d_i is the solder particle diameter, V_{xi} is the modulus of the horizontal velocity of the *ith* particle relative to the stencil, δ_i is the distance between stencil and particle surfaces, P_1 is the pressure between solder paste and stencil and α is the frictional coefficient. In Equation (3), the solder paste is treated as a pure liquid by the term following the first equal sign, as a solid liquid mixture by the term following the second equal sign and as a solid by the last term. As a solid liquid mixture, we can define the average of V_{xi} as the solder paste slipping velocity on the stencil surface. The relationship between the above terms can be explained as follows. Taking solder paste as a solid, it is easy to understand that *F* linearly increases with P_1. Taking solder paste as a solid liquid mixture, the term of the lubricating force is true only as the stencil surface is completely wetted by the flux/vehicle system. Otherwise, the interactions between some particles and the stencil would not exist, which leads to high slipping velocity. This requires that P_1 must be high enough. Taking solder paste as a liquid, similar to the solid liquid mixture, a higher slipping velocity at stencil surface leads to lower shear rate in the paste near the stencil as shown in Figure 5.

From the above analysis, it is seen that a high pressure P_1 near the slot is required to reduce the slipping velocity of solder paste on the stencil surface thus improving the aperture filling. The pressure P_1 near the slot is proportional to the pressure P loaded on the paste from the top of the chamber. Therefore, increasing P can improve the aperture filling. However, it can not completely eliminate the horizontal velocity of solder paste during the aperture filling. Loading a very high pressure on the paste is also practically difficult. CFD results also showed that there is a high-pressure region near the rear bottom corner of the chamber, which can enhance the aperture filling. However, this effect is insignificant. This is because that, as demonstrated by experiment and analysis, this pressure significantly decreases with the increase of the blade angle α. By Comparison, it is expected that the pressure near the rear bottom corner of the chamber is much lower than that near the squeegee blade tip as shown in Figure 1.

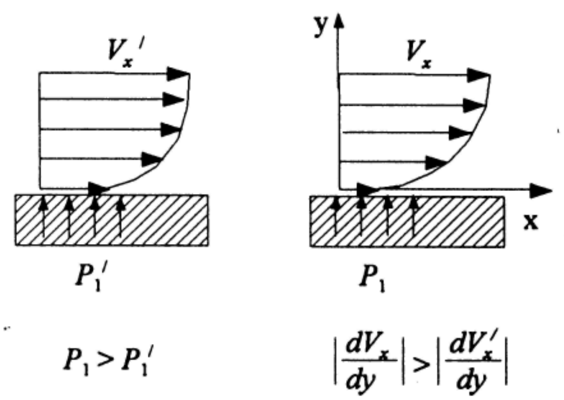

Figure 5. The shear rate in the paste near the slot.

A Proposal on Improving the Printing Process

From the above analysis it is seen that the use of the sealed printing head may suffer from the drawback of insufficient aperture filling. As the volume of paste deposit continues to decrease, this drawback becomes even more severe. To overcome it we have put forward a proposal. In this section we present our proposal and a preliminary analysis.

As analysed in the above section, the reason that causes insufficient aperture filling is the horizontal velocity component $\mathbf{V}_x$ of solder paste relative to the stencil. If the paste flow inside the chamber is merely driven by the frictional force between the stencil and the paste at the slot, this horizontal velocity is unavoidable even if there is no paste slip on the stencil surface. To counteract the influence of this undesirable velocity component, we propose to fit a horizontal shaft perpendicular to the printing direction inside the chamber as shown in Figure 6. During a printing stroke the shaft rotates inside the chamber in the printing direction to drive the paste near the slot to flow against the printing direction thus eliminating or minimising the horizontal velocity $\mathbf{V}_x$ of paste to achieve nearly vertical aperture filling. The paste velocity profile relative to the chamber is also sketched in Figure 6. It can be seen that, by introducing this shaft, the aperture filling is influenced by those parameters, the rotational speed ω, the diameter D and the position H or β of the shaft, which are analysed as follows.

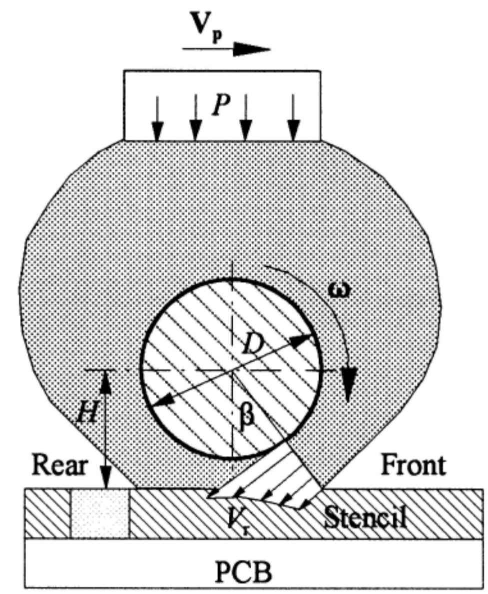

Figure 6. The proposed paste printing system.

If we ignore the slip, then the paste velocity at the shaft surface can be written as:

$$\mathbf{V}_s = \frac{D}{2}\boldsymbol{\omega} \tag{4}$$

We divide the area near the slot into three regions, region 1 is near the front of the slot, region 2 is in the middle of the slot and region 3 is near the rear of the slot. The velocity profiles are also sketched in Figure 6. In region 1 $\mathbf{V}_s$ can be decomposed into two components, $\mathbf{V}_{sx}$ and $\mathbf{V}_{sy}$, as:

$$\mathbf{V}_{sx} = \mathbf{V}_s \cos\beta = \frac{D}{2}\boldsymbol{\omega}\cos\beta \tag{5}$$

and

$$\mathbf{V}_{sy} = \mathbf{V}_s \sin\beta = \frac{D}{2}\boldsymbol{\omega}\sin\beta \tag{6}$$

From the analysis of previous section, if the parameters are so decided that $\mathbf{V}_{sx} = -\mathbf{V}_p$, then the horizontal velocity of the paste relative to the stencil is given by $\mathbf{V}_x = \mathbf{V}_{sx} + \mathbf{V}_p$ which equals zero. Thus, the paste vertically fills the aperture with velocity $\mathbf{V}_{sy}$. In region 2, $\mathbf{V}_{sx} = D\omega/2$ and $\mathbf{V}_x < 0$ which means the paste flows against the printing direction, and in region 3, the resistance of the tip of the rear side to paste flow can generate high pressure, thus enhancing the aperture filling.

Comparing with original printing head, in which the paste flow is merely driven by frictional force between the paste and stencil at the slot, in this new system, the paste flow is mainly driven by the shaft. This may significantly reduce the pressure loaded on the paste from the top of the chamber.

From Eq. (5) it is seen that, to obtain vertical aperture filling that is $\mathbf{V}_{sx} = -\mathbf{V}_p$, there are three parameters D, ω and β (or H) to be decided. We see that the paste flow in this proposed system is very similar to the eccentric cylindrical flow that has been studied by many [9-11]. We may, therefore, employ the results of these studies in the decision of the parameters of this system. Figure 7 shows two typical particle path-lines in eccentric cylindrical flow [11], in which R_o and R_i are radii of the inner and outer cylinders respectively, and e is the eccentric distance. It is seen that large eccentric distance e can cause a reversed flow in the far side from the inner cylinder. High rotational speed ω of the inner cylinder can also lead to the reversed flow. This reversed flow can cause both the solid volume fraction and the viscosity of the concentrated suspension to become inconsistent. In stencil printing, to obtain good printing quality using the proposed system it is essential that the paste flows smoothly in one direction inside the chamber. Therefore, such a reversed flow is undesirable and must be avoided in the decision of the parameters.

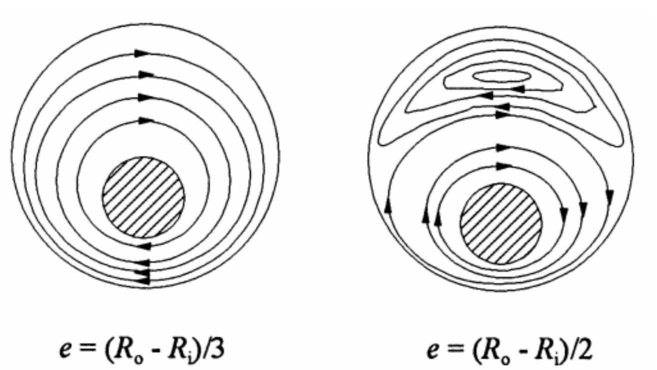

Figure 7. Particle path-lines in the eccentric cylindrical flow.

Conclusion

A study of the influence of solder paste flow inside the sealed chamber of the printing head on the aperture filling process has been presented in this paper. Our analysis shows that if the paste flow inside the chamber depends solely on the frictional force between the paste and the stencil at the slot, then the paste does not fill vertically into the aperture. The horizontal component of the paste velocity at the slot may lead to insufficient aperture filling at the trailing edge of the aperture. To counteract the influence of this undesirable velocity component, we proposed a new mechanism for improving the printing performance. The main idea is to use a horizontal shaft to drive the paste and to cause it to flow against the printing direction inside the chamber, and in this way to promote vertical aperture filling. The influences of the shaft diameter, its rotational speed and its position inside the chamber were analysed. Preliminary results show that this new mechanism can improve the printing performance of the sealed printing head. Work on the experimental validation of the physical model is underway.

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