Filling analyses of solder paste in the stencil printing process and its application to process design

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Abstract

Purpose – The purpose of this paper is to suggest an analysis methodology for the stencil printing process and to obtain proper design parameters that guarantee the successful filling using suggested finite element analyses.

Design/methodology/approach – Filling performance of solder paste in the stencil printing process is highly dependent on material properties such as viscosity and surface tension together with process parameters such as squeegee angle and squeegee speed. In order to investigate the effects of process parameters on the filling performance, the pressure built-up under the squeegee and the filling procedure of the solder paste into an aperture were analysed. Due to the limitations of the computational memory and time, the analysis domain was simplified. The pressure development under the squeegee was investigated for various values of squeegee angle and speed; then, the filling behaviour with the pressure boundary condition was analysed for only one aperture. Finally, the two analysis results were integrated to obtain the successful filling condition. In this analysis method, process parameters that guarantee filling performance were decided on.

Findings – It was shown that higher squeezing pressure develops as the squeegee angle decreases and the squeegee speed increases. The filling performance, however, improves as the squeegee angle and the squeegee speed decrease. This is because the pressure duration time decreases as the squeegee speed increases.

Originality/value – This study suggests a new design approach to obtain proper process design parameters for successful filling of solder paste into an aperture. The direct analysis of filling with squeegee movement is impossible due to limitations of computer memory and computation time. To overcome these limitations, a two steps analysis approach is proposed and can be effectively applied in the design of stencil screen printing.

Keywords Stencil printing, Solder paste, Squeegee angle, Squeegee speed, Micro bumps, Electronic engineering

Paper type Research paper

1. Introduction

These days, consumers prefer small, multifunctional electronic products such as mobile phones, and PDAs, etc. To meet such consumer requests, the components used in these products need to be small and should be assembled in high density. In the electronics industry, flip chip bonding of components with micro bumps is widely used. The bump size and pitch are critical factors in the reduction of product size. Therefore, solder paste deposition without defects is very important. Because there are difficulties in miniaturizing the components by bonding of solder balls, the screen printing of solder paste was investigated (Lee *et al.*, 2005; Durairaj *et al.*, 2008, 2009a). A schematic illustration of the stencil printing process is shown in Figure 1. In the stencil printing process, solder paste is filled into the apertures on a mask stencil (Durairaj *et al.*, 2009a). The stencil printing process has merits such as high production speed and good cost reduction. However, it is difficult to obtain a fine pitch bump array, or even bump height, due to the high viscosity and non-uniform binder size. Recently, with the development of high quality solder pastes and better printing apparatuses, the stencil printing process has been applied to fine pitch bumps (Mallik *et al.*, 2010).

In the solder paste printing process, solder paste properties, printing conditions such as squeegee speed and force and stencil design are important parameters (Haslehurst and Ekere, 1996) and many studies have been carried out. Evans and Beddow (1987) studied the particle morphology and rheological behaviour of solder pastes and they investigated the effect of shear rate of solder paste on viscosity. Kim *et al.* (2001) investigated the melting behaviour and bridging phenomena of solder pastes used in surface mount technology. They observed the shape change of solder paste during the reflow process. Tsai (2008) found the optimum conditions for the screen printing process using a response

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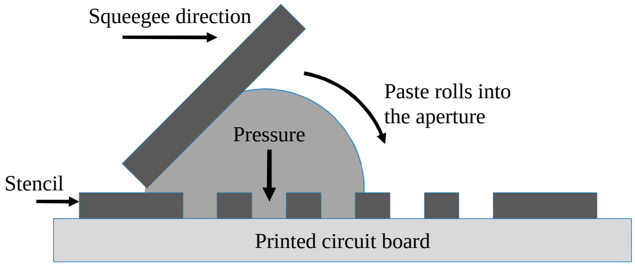
Figure 1 Schematic illustration of the stencil printing process



surface methodology and a neural network. Wang (2007) investigated the effect of rheological and wetting properties on under-fill filler settling and flow voids in flip chip packages. It was found that under-fills with small fillers had shear-thickening viscosity and yield stress.

Durairaj *et al.* (2002, 2009a, b, 2010) intensively investigated solder paste behaviour. Oscillatory stress sweep tests were performed to evaluate the solid characteristics and cohesiveness of lead-free solder pastes; creep-recovery tests were carried out to study the slump behaviour in the paste materials (Durairaj *et al.*, 2009a). They also investigated the effect of wall-slip formation on the rheological behaviour of lead-free solder pastes (Durairaj *et al.*, 2010). In addition to their experimental study, Durairaj *et al.* (2002) also carried out computer simulations to obtain a visual insight into the internal flow behaviour and the main factors influencing the printing quality. Kay *et al.* (2003, 2007) also carried out CFD analysis for the stencil printing process and obtained the printing pressure distribution for various squeegee speeds and solder paste materials. Clements *et al.* (2007) derived analytical equations for the pressure beneath the squeegee and predicted pressure distributions during steady state printing. In this study, in addition to predicting the squeegee pressure, filling analysis was also carried out. Moreover, the filling performance was predicted by integrating the results of pressure analysis and filling analysis. The effect of squeegee speed, squeegee angle and viscosity of the solder paste on the filling performance was investigated.

Recently, Seo *et al.* (2010, 2012) tried to investigate the effect of the material properties of solder paste on the filling performance in the screen printing process. They analysed the pressure built-up under the squeegee for various values of squeegee angle and the filling behaviour of solder paste into an aperture. In this study, finite element analyses were carried out for the screen printing process in the same way as in previous works, Seo *et al.* (2012). In the stencil printing process, there are so many micro-apertures on the stencil that the analysis of a full model is impossible. To analyse the filling behaviour of solder paste effectively, a global-local analysis method was employed. At first, the pressure distributions under a squeegee were calculated for various design parameters such as the squeegee angle, squeegee velocity and viscosity of solder paste. In this analysis, the small apertures were not modelled. Then, the filling behaviour of the solder paste into an aperture was analysed with the pressure boundary condition obtained in the global pressure built-up analysis. For the computational efficiency, this filling analysis was carried out for only one aperture instead of millions of apertures. Finally, the first and the second analysis results were integrated to investigate the effect of the design parameters on the filling performance.

2. Analysis of pressure built-up under a squeegee

2.1 Simplified model description

In the stencil printing process, solder paste is filled by a squeegee as shown in Figure 1. To analyse the filling behaviour of solder paste, the movement of the printing pad should be considered. The movement of the pad can be treated as a "moving boundary". Filling analysis of the solder paste into an aperture with this moving boundary condition is difficult due to geometric discontinuity. Moreover, in a stencil there are huge numbers of apertures and the filling analysis for the full model is impossible because such an analysis would require a large computer memory and long computation time. Therefore, the analyses were carried out in a global-local analysis method. In the first stage of the global analysis, squeegee pressure under a squeegee was calculated without apertures as shown in Figure 2. It was assumed that the apertures do not have an effect on the pressure built-up because the size of the aperture is very small compared to the pad size. In this pressure built-up analysis, pressure distributions for various values of squeegee angle, squeegee velocity, and viscosity of the solder paste were obtained. Then, the filling behaviour of the solder paste into an aperture was analysed, as shown in Figure 11. Tsai (2008) also found an optimum condition by filling solder paste with constant pressure instead of using a printing pad to get rid of other error factors. Finally, two analyses results were integrated to investigate the filling performance for various values of the squeegee speed, squeegee velocity and the viscosity of the solder pasts. This two-step analysis method was considered to provide more accurate solutions because numerical errors due to uneven geometry and poor mesh quality could be eliminated.

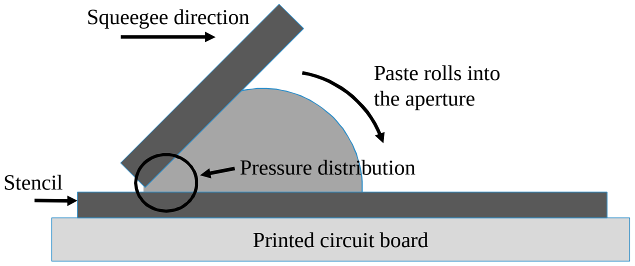
Analysis was carried out using commercial COMSOL Multiphysics^{TM} software. The first stage of the pressure built-up was analysed by a single-phase model. The governing equation and continuity equations for the single-phase flow are described as (COMSOL, 2008):

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\vec{u}\bullet\nabla\vec{u}=\nabla\bullet\left[-pI+\eta\nabla\vec{u}+(\nabla\vec{u})^{T}\right]+\vec{F} \qquad (1)$$

$$\nabla\bullet\vec{u}=0 \qquad (2)$$

In equations (1) and (2), ρ, $\vec{u}$, p, η, $\vec{F}$, and I denote density, velocity vector, pressure, dynamic viscosity, body force vector and unit matrix, respectively. The density of the solder paste was set at 4,200 kg/m^3 and analyses were carried out for

Figure 2 Simplified model for pressure built-up analysis



various values of viscosity in order to investigate the effect of viscosity on the filling behaviour. The viscosity of the solder paste is dependent on the shear rate (Durairaj *et al.*, 2002). In this study, however, the variation of viscosity with the shear rate was not considered and constant viscosity was used.

Figure 3 shows the analysis model and boundary conditions. The height and width of the solder paste were 20 and 100 mm, respectively. Through several test analyses, it was shown that dimensions higher than 20 mm of height and wider than 100 mm of width do not affect the squeeze pressure. The left inclined wall of the squeegee pad was treated as a "moving wall" boundary and a constant velocity was imposed. Analyses were carried out for various values of squeegee speed (7, 10, 15, 20, and 25 mm/s) and squeegee angle (30°, 40°, 45°, 50°, 60°, 70°, and 90°). To allow the solder paste to flow out upward or to the right, the upper and right walls were treated as a "pressure outlet" boundary and the pressure was set at atmospheric pressure. The bottom wall was treated as a "no-slip" wall boundary. To obtain accurate pressure distribution, the bottom left region, where a high pressure gradient was anticipated, was discretized by smaller elements compared to those of the other region, as shown in Figure 4.

2.2 Prediction of squeezing pressure

Figure 5 shows the pressure distribution during printing. For the results shown in Figure 5, the squeegee angle and speed were fixed at 60° and 25 mm/s, respectively; the viscosity of the solder paste was 200 Pa · s. It can be seen that the pressure was built-up only on the very small region of the bottom left. The pressure build-up procedures with time are shown in Figure 6. The pressure decreases from left to right. The pressure increased with time and finally reached a steady state in the very early stage of printing at 1.3 ms. Figure 7 shows the pressure distribution near the pad when the printing times were 2.0 and 500.0 ms. In both cases, the distance between the pressure of 30 and 100 kPa was 0.75 mm. Figures 6 and 7 show that the pressure distribution reached a steady state in the early stage of printing (1.3 ms).

To investigate the effect of the viscosity of the solder paste on the squeegee pressure, analyses were carried out for various values of viscosity between 10 and 250 Pa · s. Figure 8 shows the results. It can be seen that higher pressure is built-up as the viscosity increases. When the viscosity was 10 Pa · s, very low pressure was built-up. Figures 9 and 10 show the effect of the squeegee angle and the squeegee speed on the pressure development. As expected, higher pressure developed as the squeegee angle decreased and the squeegee speed increased. In Figure 9, it is also shown that the pressure develops in a wider region as the squeegee angle decreases. This means that the solder paste can be pressed into an aperture in a sufficiently long time. As a result, the effects of the viscosity of the solder paste, the squeegee angle and the squeegee speed on the pressure development were investigated quantitatively.

Figure 3 Dimensions and boundary conditions for pressure built-up analysis

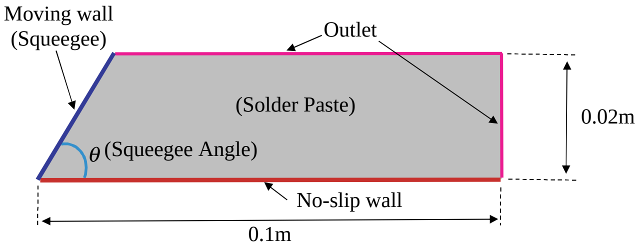
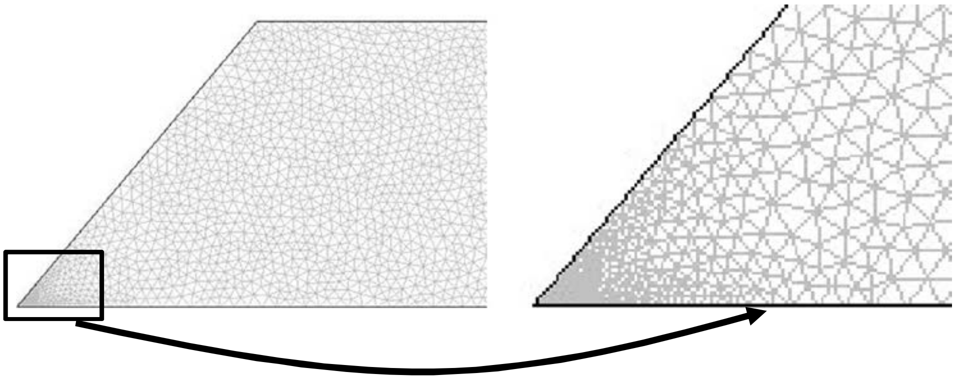


Figure 4 Element discretization for simplified analysis



3. Filling analysis into a micro-aperture

3.1 Analysis model description

To investigate the filling performance of the solder paste into apertures, filling analyses were carried out for various values of pressure. For computational effectiveness, only one aperture was subjected to the analysis, as shown in Figure 11 (Seo *et al.*, 2010). By assuming a cylindrical aperture, analysis was carried out in an axisymmetric model. Figure 11(a) shows the initial state of the solder paste and Figure 11(b) shows the filling of the solder paste schematically. The analysis model is shown in Figure 12. Initially, the aperture was filled with air and constant pressure was imposed on the upper boundary with a "pressure inlet" condition. A solder paste thickness of 40 μm is sufficient because the solder paste continuously flows in through the boundary of the pressure inlet. The inside walls of the aperture were set as "wetted walls". To allow the inside air to flow out, the bottom right wall of 5 μm was set as a "pressure outlet". During the filling of solder paste, the inside air flows out through the small gap between the stencil and the printed circuit board. To allow for this air vent, 5 μm of vent was modelled on the corner as shown in Figure 12. The effect of the vent size on the filling performance was not investigated because the viscosity of air is very low compared to that of the solder paste and the solder paste reaches the region at the final stage of filling. Therefore, it is considered that vent size does not have an effect on the filling performance.

Figure 5 Distribution of pressure obtained with simplified model

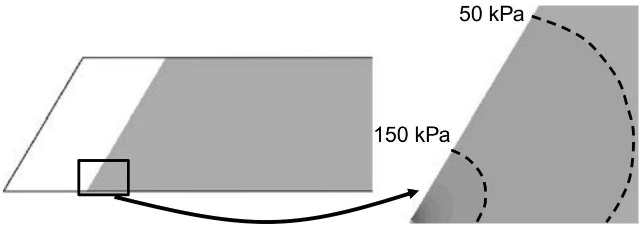
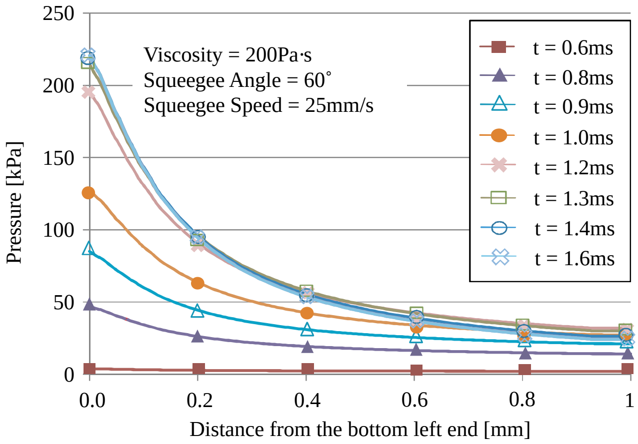
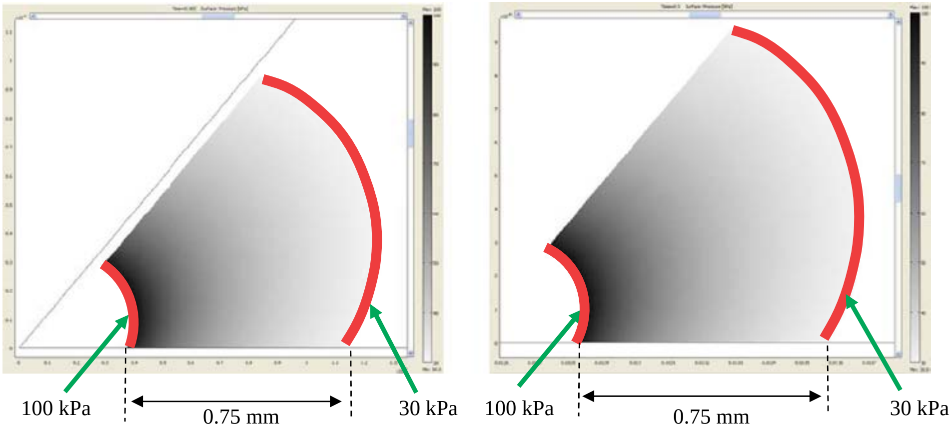


Figure 6 Pressure distribution under the pad at several squeegee time that shows the pressure built-up procedure



Notes: Viscosity = 200 Pa · s, squeegee angle = 60°, squeegee speed = 25 mm/s

Figure 7 Distance between points of 30 and 100 kPa at elapsed time of (a) 2.0 and (b) 500 ms



(a) (b)

This filling analysis is a two-phase flow problem. The governing equation and the continuity equation for the two-phase flow with gravity and surface tension are given as:

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\vec{u}\bullet\nabla\vec{u}=\nabla\bullet\left[-pI+\eta\nabla\vec{u}+(\nabla\vec{u})^{T}\right]+\vec{F}+\rho\vec{g}+\vec{F}_{ST} \tag{3}$$

$$\nabla\bullet\vec{u}=0 \tag{4}$$

In equation (3), $\vec{g}$ and $\vec{F}_{ST}$ are a gravity vector and a surface tension vector, respectively. The density and viscosity of air were set at 1.225 kg/m^3 and 0.00002 Pa · s, respectively. For the density of the solder paste, a value of 4,200 kg/m^3 was used (Nihon Genma Mfg. Co. Ltd, 2011). For the surface tension and contact angle of the solder paste, the values of 0.1-0.5 N/m (Howell *et al.*, 2004) and 60° (Hsieh *et al.*, 2009) were used, respectively.

3.2 Analysis results of filling behaviour

Figure 13 shows the filling shapes with time for various squeezing pressures. Figure 13(a) and (b) are the analysis

Figure 8 Pressure distribution for various values of solder paste viscosity

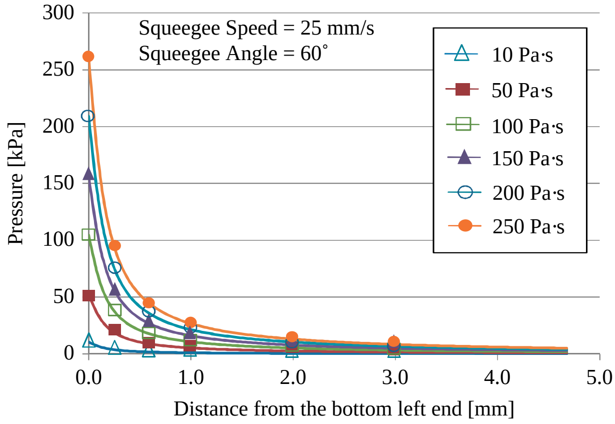


Figure 9 Pressure distribution for various values of squeegee angle

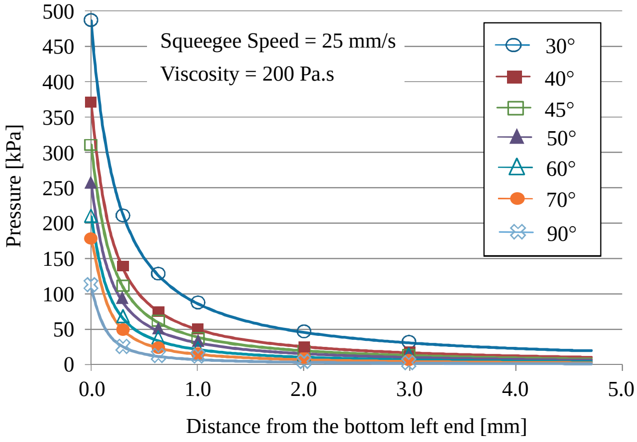


Figure 10 Pressure distribution for various values of squeegee speed

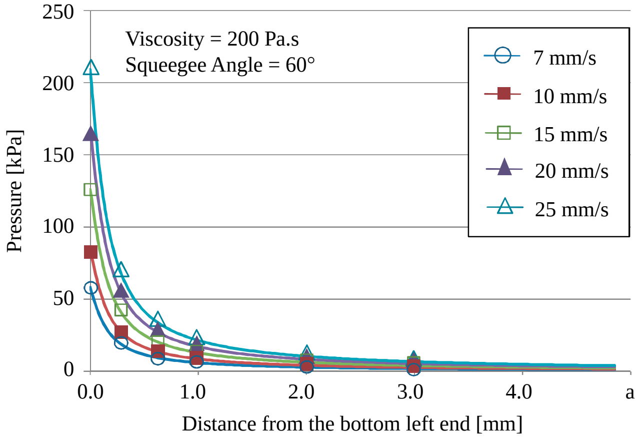
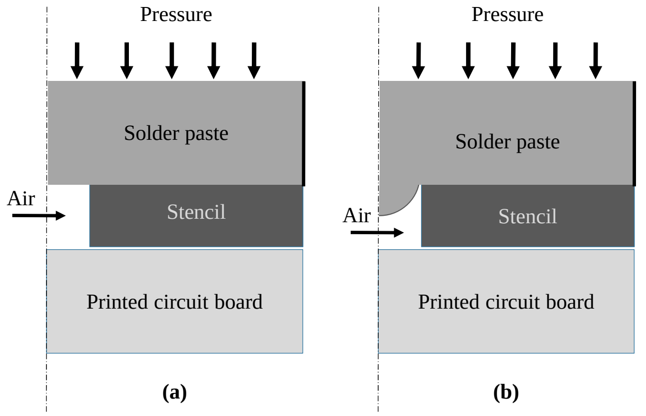
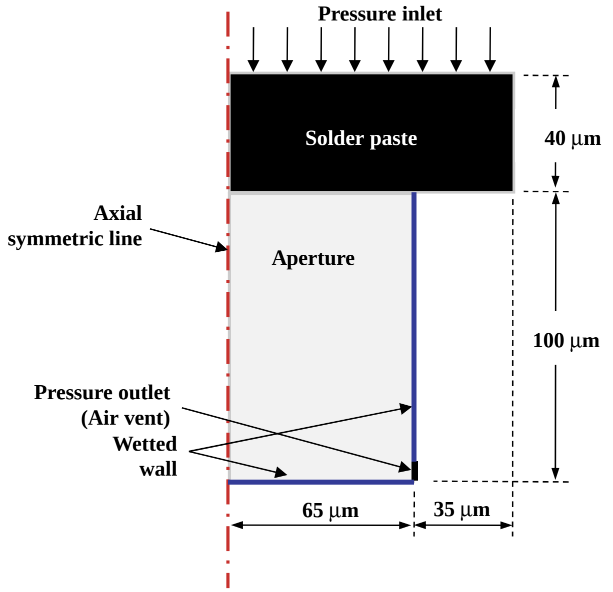


Figure 11 Simplified two-dimensional axisymmetric model for filling analysis



Notes: (a) Initial condition and (b) the filling stage

Figure 12 Dimensions and boundary conditions for two-dimensional axisymmetric filling analysis

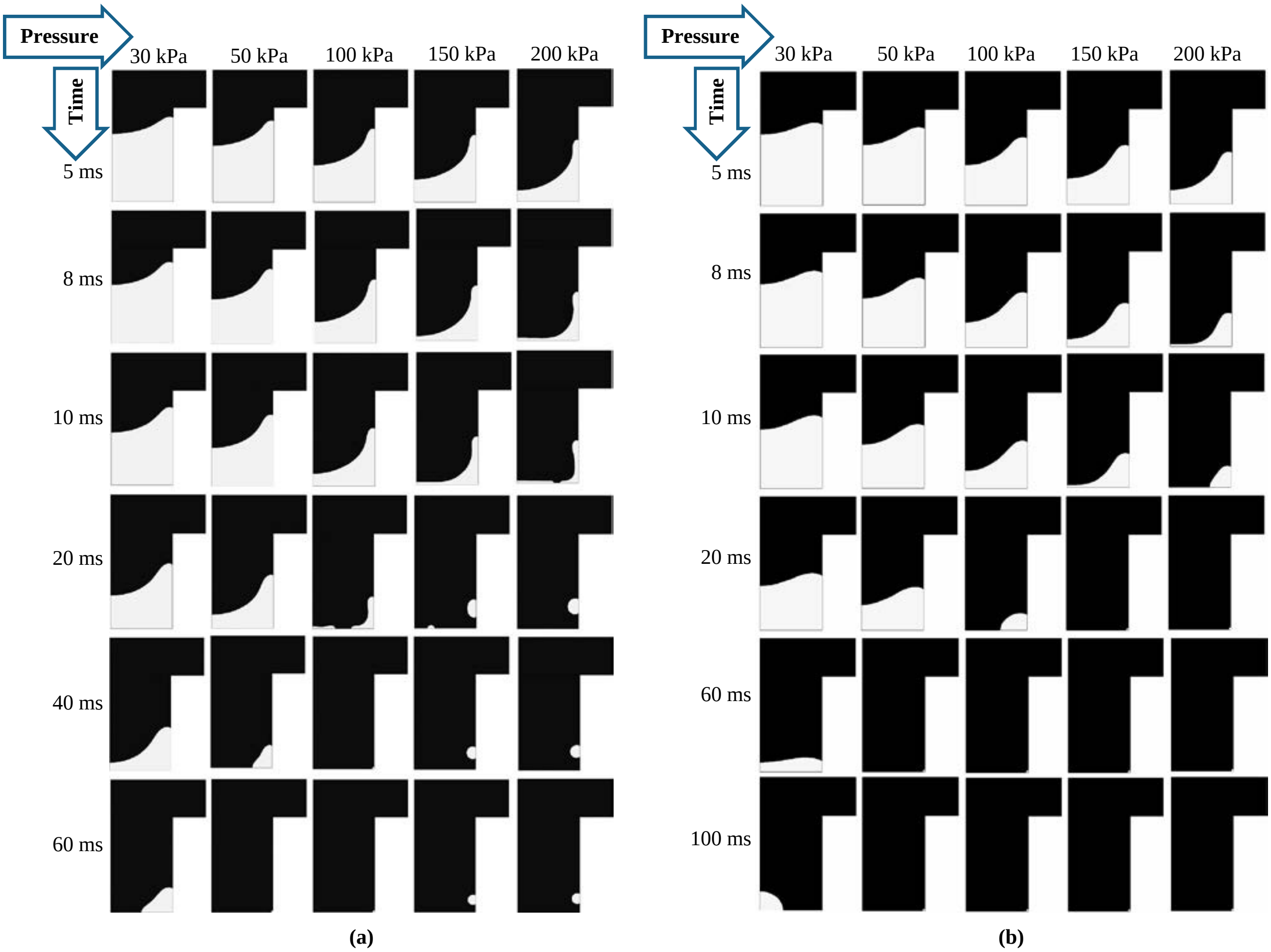


results for surface tensions of 0.1 and 0.5 N/m, respectively. Solder paste flows faster into the aperture as the pressure increases. It is also shown that the filling shape is highly affected by the surface tension. When the surface tension of the solder paste is 0.1 N/m, the filling speed on the wall is slower compared to that of the central region and this causes void generation on the bottom left corner when inlet pressure is greater than or equal to 150 kPa. When the surface tension of the solder paste is 0.5 N/m, the filling speed on the wall is relatively faster than in the case of 0.1 N/m of surface tension. Especially, when the surface tension is 0.5 N/m and the inlet pressure is 30 kPa, a void is generated on the bottom central region due to the high filling speed on the wall. These results show that the filling performance is highly dependent on the squeezing pressure and solder paste properties.

The filling ratio defined in equation (5) was monitored with time in order to investigate the filling performance quantitatively:

$$\eta = \frac{V_{Paste}}{V_{Aperture}}. \qquad (5)$$

Figure 13 Filling shapes for various values of inlet pressure and filling time



Notes: (a) Surface tension = 0.1 N/m; (b) surface tension = 0.5 N/m

In equation (5), V_{Paste} denotes the volume of paste filled in an aperture and $V_{Aperture}$ is the volume of the aperture. Figure 14 shows the filling ratio with time for the results shown in Figure 13. In these analyses, the viscosity and contact angle of the solder paste were fixed at 200 Pa · s and 60°, respectively. As expected, the filling speed increased as the squeezing pressure increased in both cases. When the surface tension was 0.1 N/m, the aperture was not fully filled when the squeegee pressure was greater than or equal to 150 kPa, due to the void generation near the wall (Figure 13(a)). When the surface tension was 0.5 N/m (Figure 14(b)), however, under-fill took place in the case of a low squeezing pressure of 30 kPa, due to void generation on the bottom central region (Figure 13(b)). These voids can cause delamination defects.

4. Parameter study for printing conditions

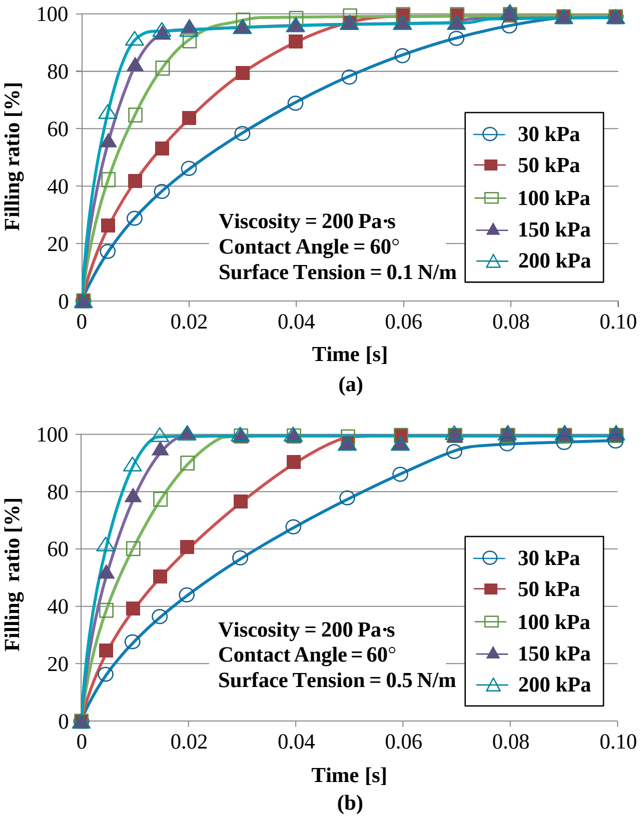
For the exact prediction of the filling behaviour of solder paste according to squeegee speed and angle, the pressure value on the top of the aperture has to be monitored with time and the time dependent pressure has to be imposed as the boundary condition. However, the monitoring and imposition of the time dependent pressure boundary condition is time consuming. In this analysis, therefore, a simplified approach was adopted instead of using the time dependent pressure boundary condition, with the following assumptions.

- Solder paste starts to flow into an aperture when the pressure reaches a certain value (P_S in Figure 15(c)) such as 30 kPa or 100 kPa. The schematic illustration for this assumption is shown in Figure 15. P_S is the pressure value over which solder paste starts to flow-in. Solder paste may start to flow into an aperture with a squeegee pressure lower than this assumed pressure. So, this assumption makes the design more robust.
- The squeegee pressure remains constant until the pad has completely passed the aperture. As shown in Figure 15(c), pressure increases as the squeegee pad comes closer to the aperture. Therefore, a process design with this assumption is also more robust.

With the previous assumptions, solder paste starts to flow into an aperture when the squeegee pad is located as shown in Figure 15(a) and the filling finishes when the squeegee pad is located as shown in Figure 15(b). Therefore, the pressure duration time for filling is calculated as:

$$t_{duration} = \frac{L_P + L_A}{V_S}. \tag{6}$$

Figure 14 Filling ratio of solder paste for various values of inlet pressures



Notes: (a) Surface tension = 0.1 N/m; (b) surface tension = 0.5 N/m

Figure 15 Schematic illustrations of (a) beginning and (b) finishing stage of filling and (c) the squeegee pressure used in the analysis

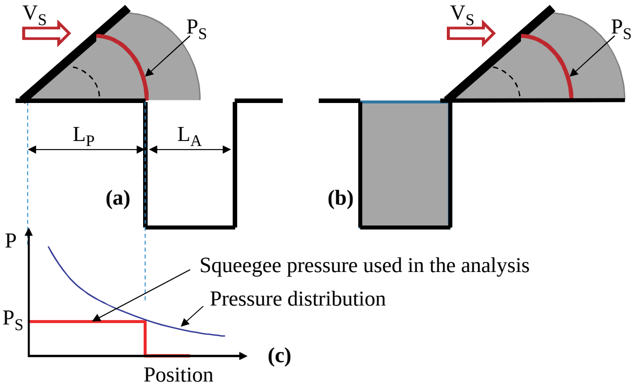
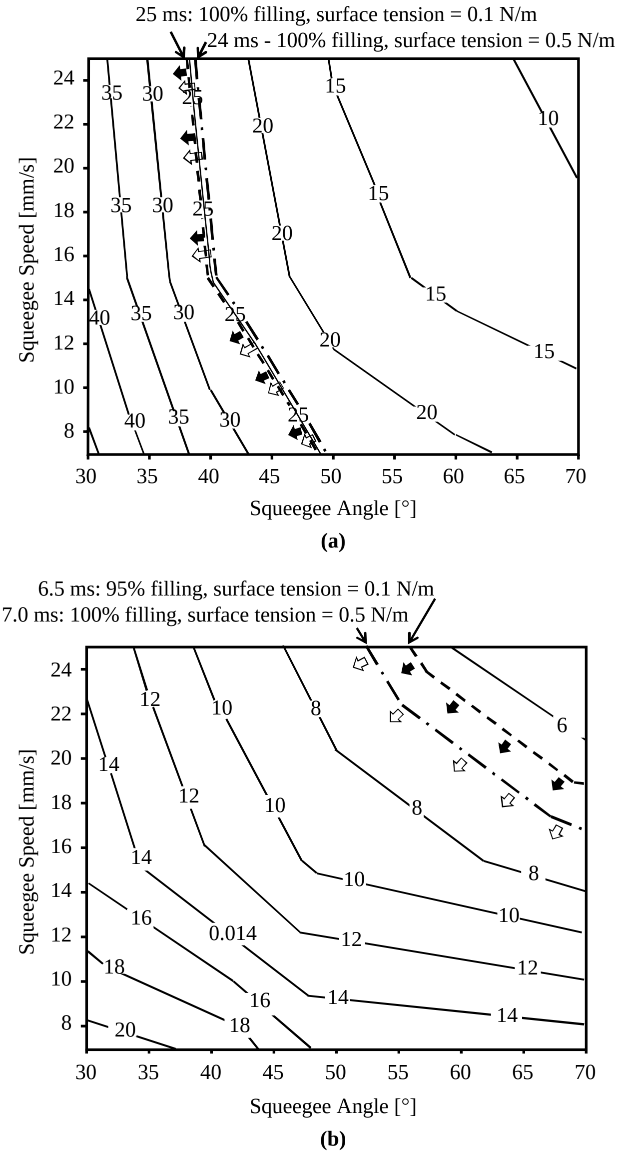


Figure 16 Contour of pressure duration time for solder paste filling and recommended process conditions for successful filling (viscosity = 50 Pa · s): pressure duration time is calculated for the region over (a) 30 kPa and (b) 100 kPa

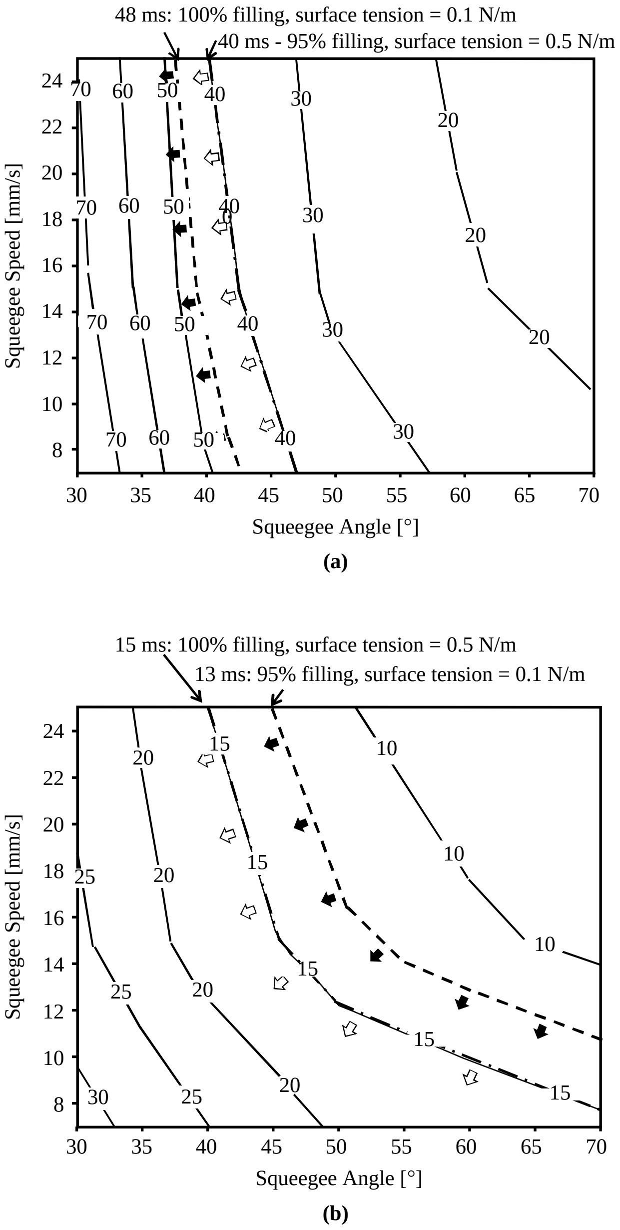


In equation (6), L_P is the distance from the squeegee pad to the point where a certain value of pressure (P_S) is developed, as shown in Figure 15(a). L_A is the diameter of the aperture and V_S is the squeegee velocity.

Two pressure values, 30 and 100 kPa, were chosen as P_S over which the solder paste starts to flow-in and the results were compared. The values of L_A were measured from the analysis results discussed in Section 2.2 for various values of squeegee angle and velocity. Figures 16-18 show the contour for the pressure duration time, calculated by equation (6), for various values of squeegee angle, squeegee speed, and solder paste viscosity. In the pressure built-up analysis that is mentioned in Section 2, the effect of surface tension on the pressure development is negligible because the analysis domain is large compared to that of an aperture having micro-dimensions. Therefore, the pressure duration time calculated for the surface tension values of 0.1 and 0.5 N/m were almost the same and are plotted in one figure.

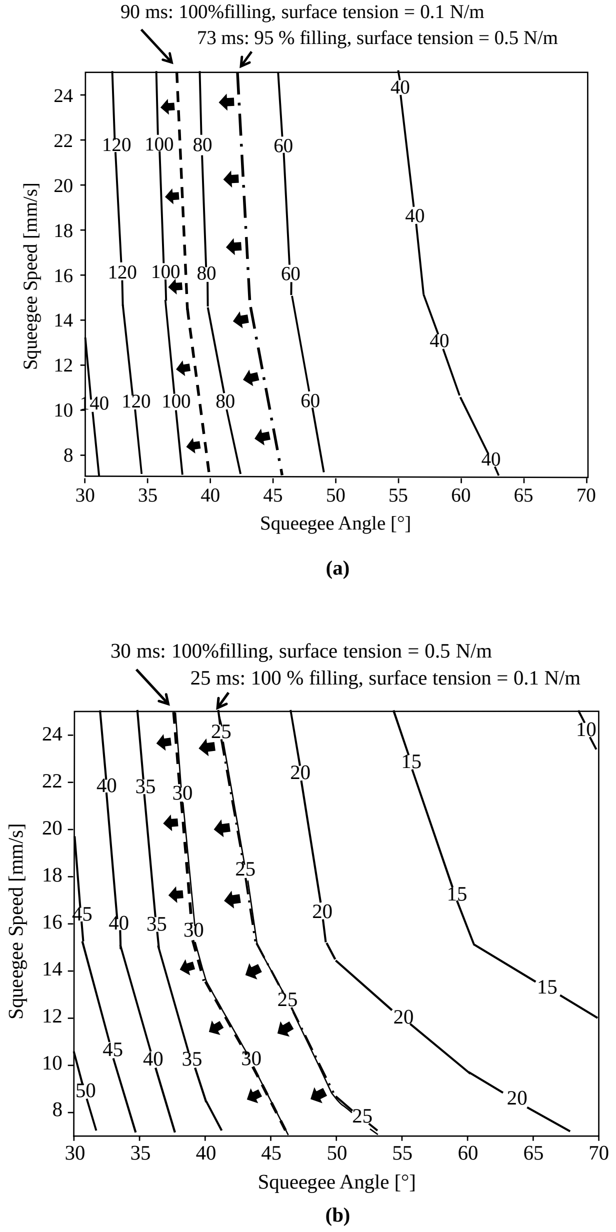
To investigate the process conditions for 100 per cent filling, the required pressure duration time was determined for various values of surface tension and viscosity from the results of the filling analyses shown in Figure 14. In the case of void generation, 100 per cent filling was impossible; therefore, the required filling time was determined to be that

Figure 17 Contour of pressure duration time for solder paste filling and recommended process conditions for successful filling (viscosity = 100 Pa · s): pressure duration time is calculated for the region over (a) 30 kPa and (b) 100 kPa



of 95 per cent filling instead of 100 per cent filling. The left region of the solid arrow shows the design region in which 100 per cent filling can be obtained for the case of 0.5 N/m of surface tension. The region left of the white arrow shows the design region in which 100 per cent filling can be obtained for the case of 0.1 N/m of surface tension. When the inlet pressure is 30 kPa, the solder paste fills the aperture faster in the case of 0.5 N/m of surface tension than in the case of 0.1 N/m of surface tension. When the inlet pressure is 100 kPa and the viscosity of the solder paste is lower than or equal to 100 Pa · s, however, the filling is faster in the case of 0.1 N/m than in the case of 0.5 N/m. Figures 16(b), 17(b) and 18(b) show that the filling completes slowly as the viscosity of the solder paste increases.

Figure 18 Contour of pressure duration time for solder paste filling and recommended process conditions for successful filling (viscosity = 200 Pa · s): pressure duration time is calculated for the region over (a) 30 kPa and (b) 100 kPa



As a result, the process conditions for successful filling for various material properties of solder paste could be obtained from Figures 16 to 18. Successful filling of the solder paste could be obtained in the case of low squeegee angle and low velocity. This is an important viewpoint. Higher squeegee velocity builds up higher squeezing pressure, as shown in Figure 10. The filling performance, however, deteriorates as the squeegee velocity becomes higher. This is because the pressure duration time decreases as the squeegee velocity increases. The successful filling regions obtained with inlet pressure of 100 kPa and pressure duration time over 100 kPa (Figures 16(b), 17(b), and 18(b)) are wider than the successful region obtained with inlet pressure of 30 kPa and pressure duration time over 30 kPa

(Figures 16(a), 17(a), and 18(a)). The design conditions shown in Figures 16(b), 17(b), and 18(b), therefore, are preferable.

5. Conclusions

The effect of process conditions such as squeegee angle, squeegee velocity and material properties on the stencil printing performance were investigated by finite element analysis. Due to the limitations of computer memory and computation time, analyses were carried out in a global-local two-step method. In the first stage, the pressure built-up under the squeegee was predicted by the simplified model without considering the filling into apertures. Then, the filling phenomena were analysed with the pressure obtained in the first stage. Using this two-step analysis method, it was possible to analyse the stencil printing process efficiently, and the following conclusions were derived:

- It was shown that the squeezing pressure reached a steady state just after the squeegee moved. The effects of squeegee angle, squeegee velocity and viscosity of the solder paste on the squeezing pressure were investigated. The higher squeezing pressure was developed with the smaller squeegee angle, with the higher velocity, and with the higher viscosity of the solder paste.
- In the filling analysis of the solder paste, it is shown that voids can be generated in an aperture in the case of low surface tension (0.1 N/m) and high squeezing pressure (greater than or equal to 150 kPa). Voids can also be generated in the case of a high surface tension of 0.5 N/m and low squeezing pressure of 30 kPa. For the filling of solder paste without voids, a squeezing pressure between 50 and 100 kPa is recommended.
- The values of squeegee angle and velocity for successful filling of solder paste were obtained for various values of viscosity and surface tension. It is shown that a higher velocity of the squeegee pad is not always good. Although a higher pressure was built-up under the squeegee with a higher squeegee velocity, the filling performance deteriorated at the higher squeegee velocity due to the short pressure duration time.

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