Effects of Different Viscometer Test on Stencil Printing Process for CFD Simulation

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Effects of Different Viscometer Test on Stencil Printing Process for CFD simulation

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Abstract

This study discusses the use of different spindle type for the testing of lead-free solder paste by using Computational Fluid Dynamics (CFD) simulation. The study focuses on measuring the volume of solder paste deposition on the solder pad. Parallel-plate (PP) and Cone-plate (CP) spindle were used with five different tests consist of different spindle type and setting. The Volume of Fluid (VOF) method was used for the simulation while Cross model was applied as viscosity model for the solder paste. SAC305 type 3 lead-free solder paste was used in this study as it is mostly popular used by the industries nowadays. The solder paste filled the volume under different squeegee speeds and aperture size was compared between experiments and simulations. For different squeegee speed, PP 0.5 mm gap obtained the lowest average discrepancy value between simulation and experimental results. At different aperture size, all test show similar trend line and about the same value of average discrepancy with CP1° while PP 0.5 mm gap showed the lowest average discrepancy. At small aperture volume, all tests performed shows similar value of filled volume except PP 0.5 mm which exhibit the lowest percentage difference when compared with the experimental values at a bigger aperture volume.

Keywords: SAC305, lead-free solder paste, Stencil Printing, Viscometer, SMT Simulation

1.0 Introduction

Electronic items continue to improve and grow increasingly sophisticated throughout time. Become both smarter and smaller. This advancement must be accompanied by advancements in the manufacture of electronic components. The electronics industry uses Surface Mount Technology (SMT) to manufacture electronic boards. The procedure entails a number of steps starting with a plain Printed Circuit Board (PCB) and ending with a PCB that filled with electronic components.

The stencil printing method is the first step in the procedure. This method involves solder paste deposition technique on the solder pad by using a stencil. The technique performed utilises an angle-moving squeegee to ensure solder paste sweeping perfectly into the desired aperture as shown in Figure 1. This procedure amounts roughly about 60% of failure and faults in SMT manufactured products [1]. Overall costs related to designing and testing experimentally for stencil printing processes usually include both money and time. Therefore as an alternative method, the integration of numerical simulation such as Computational Fluid Dynamics (CFD) particularly, demonstrates profound analysis and results to investigate the characterization of solder paste stencil printing process.

Krammer [2] used the Finite Volume Method (FVM) to compare the simulation of stencil printing between non-Newtonian model and Newtonian model for solder paste. From the research made, it was concluded that the solder paste must be simulated by using a non-Newtonian model. Calculation errors will occur if the solder paste true material properties are not utilised. Besides that, Manassis et al. [3] performed a CFD technique to determine the correlation between squeegee speed variation and solder paste density. When the squeegee speed increased, shear tension and strain will also increased.

Durairaj et al. [4] also employed a two-dimensional (2D) CFD technique to examine the flow characteristics of lead-free and lead-containing solder pastes. Their method revealed solder paste characterization and rheological research, in conjunction with computational simulations, provide hitherto an unavailable insight into the stencil printing process mechanism. Rusdi et al.[5] has created a three-dimensional (3D) computer simulation for estimating the amount of solder paste that is printed via stencil. The numerical simulation was performed by using a combination of cross viscosity model and volume of fluid (VOF) method. A SAC305 solder paste of type 3 which is widely used in industry standard, was used. It was discovered that the experiment and simulation results for solder paste filling volume are comparable. Different aperture sizes produced comparable results, and experimental findings are in agreement. Furthermore, Thakur et al. [6] also perform a research study on the effects of process parameters that impact the stencil printing process by using the CFD approach. In this study, Sn3.5Ag solder paste was used. It was discovered that higher squeegee speed results in larger shear stress values, so the shear strain rate of solder paste also increases proportionately thus causing the solder paste to be apply easily and completely fills the gap. The consistency of solder paste filling is therefore crucial in stencil printing.

In order for the simulation of stencil printing process to be executed optimally, it require the inclusion of solder paste material characteristics within the simulation model, particularly its viscosity qualities. Other than that, solder paste also possess a variety of material properties such as non-Newtonian fluid, thixotropic fluid, and shear thinning behavior [7]. Moreover,

increased in shear tension applied to the solder paste will reduce its viscosity. Prior to this technique, past researchers have used a variety of methods to determine and analyze the viscosity of their solder paste sample such as by using a viscometer to measure fluid viscosity.

Zhang et al. [8] select a 25 mm diameter parallel plate with a 0.55 mm gap to investigate the relationship between viscosities and particle size distributions for lead-free solder powders (Sn/Ag/Cu). Amalu et al. [9] evaluated three alternative Pb-free solder pastes for use in ultra-fine pitch assembly. The viscosity test was performed with shear rates ranging from 0.001 to 10. The findings suggest that the printing process variables and their interactions played a substantial role in paste transfer efficiency. Dusek et al. [10] investigated SAC305, SAC405 and Sn62Pb36Ag2 using a 24 mm diameter cone-plate spindle set to a 1.565° angle. From the findings obtained, it is indicated that the viscosity of solder pastes decreases by half over time when the measurements begin from almost-stored temperatures and end at ambient temperatures.

Min-Jung Son et al. [11] compared between microparticles and nanoparticles lead-free solder pastes that will be employed in the construction of solder bump arrays using roll-offset (RO) printing. The rheological properties of SAC solder pastes are determined using a rotational rheometer with a 1° cone-and-plate configuration. The cone gap width and diameter are 0.052 mm and 60 mm respectively. Mallik et al. [12] investigated the rheological properties of four different particle sizes, metal alloys, and alloy compositions of no-clean flux solder using a serrated parallel-plate spindle. The solder paste was evaluated for flip-chip assembly. A series of printing tests was performed to determine the relation between rheological properties of the solder paste and the printed results.

The CFD simulations require the inclusion of rheological data in the material properties of the solder paste. The viscosity data is critical to ensuring that the CFD simulation accurately predicts the solder paste flow. Due to the fact that earlier researchers used a variety of test methods, it is critical to select the most appropriate spindle type for solder paste measurement. The purpose of this study was to investigate the impact of spindle type on CFD simulations. Various viscosity data will be inserted into the CFD model to assess which viscosity data is the most suitable for predicting the filled volume using CFD. The CFD simulation results will be compared against experimental data. The experimental results were obtained by utilizing an industrial stencil printing machine while the volume of solder paste deposition was measured by using a 3D scanner on the Celestica Malaysia SMT line. This study analysis will contribute to assist the researcher in selecting the appropriate viscosity test for CFD simulation. Additionally, all experimental work is undertaken on an actual SMT machine. In response to the growing demand for environment friendly components, this study will utilise SAC305, a specific type of solder paste which is lead-free and used popularly by manufacturers and researchers alike. Stannum, Silver, and Copper are the core material used in the solder paste.

2.0 Methodology

2.1 Viscosity Test

The viscosity of solder paste was determined by using an Anton Parr viscometer (Figure 2). Three types of spindle was used at 1.014° Cone plate, 2° Cone Plate and Parallel Plate. The gap heights of the 1.014° Cone plate and the 2° Cone plate were fixed, while the gap heights of the Parallel Plate were adjusted (Table 1). The gap height was defined as the distance between the fixed plate and the spindle plate (below and top). While the bottom plate was fixed during the testing, the spindle will rotate at a specific speed to control the shear rate. The test was conducted at shear rates ranging from 0.001 s⁻¹ to 10 s⁻¹ [12]. At room temperature (25 ± 2 °C), the viscosity tests were conducted. Figure 3 illustrates the difference between a Parallel Plate and a Cone Plate spindle. The viscosity and shear rate data are then transferred to the WinRheo software for the Cross model values to be calculated. The SAC305 type was chosen for this experiment because it is the industry preferred lead-free solder paste. The solder paste was supplied by Indium Corporation.

2.2 Stencil Printing Process Experiment

The experimental work were performed by using an industry solder paste printing machine DEK265. The squeegee was placed at an angle of 60° with squeegee load of 9 kg and moved at a constant speed of 35 mm/s [13]. The solder pastes then measured by using Koh Young Aspire 2 3D scanner. The experiments of stencil printing process were conducted in a room temperature of (25 ± 2 °C) at Celestica Malaysia. A stainless steel stencil was used with a dimension of 730 mm × 735 mm and a thickness of 0.127 mm while the squeegee was fixed at 60° angle.

2.1 Numerical Simulation

ANSYS Fluent version 19 was selected as the numerical simulation software that will be used in this study. ANSYS Fluent is an acceptable computational fluid dynamics (CFD) software with precise calculations that able to simulates stencil printing process using the Finite Volume Method (FVM). The Navier–Stokes technique was applied in this study, where the procedure of SAC305 solder paste being filled into the stencil aperture can be calculated and analyzed by the governing equations of mass, momentum, and energy conservation.

The conservation of mass or continuity equation is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2.1)$$

Eq. (2.1) is the mass conservation equation in which it is valid for incompressible flow.

The Conservation of momentum equation in x -, y - and z -direction is written as:

$$(x\text{-direction}) \quad \rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial P}{\partial x} + \eta \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2.2)$$

$$(y\text{-direction}) \quad \rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial P}{\partial y} + \eta \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (2.3)$$

$$(z\text{-direction}) \quad \rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial P}{\partial z} + \eta \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (2.4)$$

where P is the static pressure, ρ is density, η is the viscosity and u, v, w is the velocity in x -, y - and z - direction.

The conservation energy equation can be described as:

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \eta \dot{\gamma} \quad (2.5)$$

where k is the thermal conductivity, T is the temperature, η is the viscosity and $\dot{\gamma}$ is the shear rate, respectively.

The rheological behaviour of the solder paste was investigated by using the Cross model viscosity model [14]. With the Arrhenius temperature dependence, the solder paste is assumed and described as GNF when using the Cross model as the viscosity model.

$$\eta(T, \dot{\gamma}) = \frac{\eta_0(T)}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\tau^*} \right)^{1-n}} \quad (2.6)$$

with

$$\eta_0(T) = B \exp \left(\frac{T_b}{T} \right) \quad (2.7)$$

where B is an Exponential-fitted constant, T_b is the temperature-fitted constant, n is described as the power law index, η_0 is designated as the zero-shear viscosity and τ^* refer to a parameter that explain the transition region that exist between power law region of the solder paste viscosity curve and the zero shear rate.

The VOF method was utilized to locate the existence and distribution of liquid phase by appointing each cell within the computational grid with a scalar (f). f is the fraction of cell volume occupied by liquid. Thus, f will equal to 1 ($f = 1$) when the cell filled with solder paste only while f will equal to zero ($f = 0$) in cell which consist of air and when f is between 0 and 1 ($0 < f < 1$) it is solder paste front (interface cells). The equation that governed the description of melt front over time is as follows:

$$\frac{dF}{dt} = \frac{\partial F}{\partial t} + \nabla \cdot (uf) = 0 \quad (2.8)$$

By using VOF, air and solder paste were defined as two different phases of fluid in the simulation. The squeegee was marked as a moving wall where the movement of the squeegee at a certain speed use a dynamic mesh. During movement of the squeegee, the solder paste will move forward and filled the aperture. In the meantime, the air will move out through the outlet vents. In the FLUENT analysis, the symmetry walls, pressure outlet and moving wall boundaries were defined in the computational domain. Figure 4 depicts the boundary conditions of the 3D simulation model.

3.6 Grid independence & time step test

The time step size and grid size are critical in numerical simulation analysis because they will influence the experiment results to be either overestimated or underestimated. Thus, five different time-step sizes (0.01, 0.05, 0.001, 0.005 and 0.0001) with a computational domain of 2632 hexagonal elements were tested to get the best simulation predictions. The experiments were carried out under constant stencil printing process parameters (9 kg squeegee load, 35 mm/s squeegee speed, and 0.3 mm/s separation speed), which is representative of actual process circumstances. The volume of solder paste between numerical prediction and experiment was examined for validation purposes, as shown in Table 2. The results indicated that all numerical simulations overestimated the volume of solder paste. However, when the 0.001-time step size was used as in Case 3, 7.4 percent of error was reported. Therefore, Case 3 with a time step size of 0.001 was chosen for further examination since it had the smallest inaccuracy in comparison to the experimental results. In instance 3, Figure 5 illustrates the experimental measurement and simulation outcome.

Five distinct hexagonal mesh element counts were determined to performed grid independence test. The simulation results obtained were compared to the volume of solder paste in the aperture acquired through experiment work. The findings comparison between experimental results and simulation data is summarized and tabulated in Table 3. Case 2 has the smallest error with 2632 elements, followed by Case 3 and Case 5 with 3712 and 7072 items, respectively. Based on the time step and grid independency tests, a computational domain with 2632 elements and a time step of 0.001 was chosen for further investigation and analysis.

3.0 Results and Discussion

3.1 Effect of Different Spindle for Measuring

In this study, five different spindle tests were investigated with two types of spindle being used. The PP was set at three different plate gaps of 0.25 mm, 0.5 mm, and 0.75 mm. Two CP spindle were used with an angle of 1° and 2°. From Figure 6, CP 1° shows the highest viscosity value compared to other tests. PP 0.25 mm and PP 0.5 mm obtain roughly the same value of viscosity throughout the shear rate range. Meanwhile, CP 2° and PP 0.75 mm have similar viscosity value. CP 1° is expected to have the highest viscosity values because it has the smallest plate gap of 0.051 mm. The PP 0.25 mm and PP 0.5 mm are the same type of spindle with a small different gap. CP 2° have a small gap of 0.104 mm but have the same viscosity value to the largest gap of PP 0.75 mm. The small gap of 0.104 mm is measured between the tip of the cone and the fixing plate. At the end of the spindle, the gap is actually 0.453 mm. This is believed to occur due to larger gap have lower axial stress thus the measurement taken from larger gap spindle show lower viscosity values.

3.2 Effect of Different Squeegee Speed

The spindle tests than being compared with the experiment at different squeegee speed. Figure 6 shows the result of the volume of aperture filling with solder paste at different squeegee speed. It can be seen in Figure 7 that the simulation is underpredicted the experiment results. Only PP 0.5 mm and CP 2° show similar trend except at 55 mm/s as PP 0.5 mm have the same result to its 45 mm/s value. Further examination of the CP 2° showed a slight decrease value than its 45 mm/s.

Figure 8 depicts the difference of solder paste volume between the simulation and the experiment in percentage. It can be seen that for different squeegee speed, PP 0.5 mm gives the lowest average discrepancy at 5.4% and CP 1° exhibits the highest average discrepancy at 6.1%. Similar findings have been observed in other studies except for CP 1° where the highest difference is at 25 mm/s. Nevertheless, all the tests showed similar values at the lowest difference, 55 mm/s. This could be attributed to lower viscosity at higher squeegee speed. The results obtained agreed with Fig 5 where at higher shear rate (higher spindle speed), the viscosity at all spindle tests obtain quite similar findings.

3.3 Effect of Different Aperture Size

Figure 9 shows the aperture size results at three different aperture volumes (0.09 mm³, 0.33 mm³ and 0.82 mm³). The squeegee speed is fix at 35 mm/s for all spindle tests. As can be seen in figure 9, similar trends have been observed in all tests as the experiment and the volume of all test's values are close to each other. This similar trend was also in general agreement with Fig. 8 where at 35 mm/s squeegee speed the values between different spindle test are close to each other. It can be seen that the solder pastes volumes increased as the aperture volume increased from 0.1 mm³ to 0.8 mm³. At lower aperture volume, the difference is smaller between the experimental and simulation values. The difference increases with the increase of

aperture volume. By referring to Figure 10, the volume percentage difference on the aperture volume decreased gradually when the aperture volume increase. PP 0.5 mm and CP 1° give the lowest percentage difference at 11.6%. Figure 11 shows a clearer view on volume difference where at lower aperture volume, the solder paste volume with different viscosity test gives about the same volume of solder paste. When the aperture volume increase, PP 0.5 mm gives a better result with lower volume difference than other viscosity tests.

4.0 Conclusions

PP and CP spindle were used with five different type of test method. PP was varied at 0.25 mm, 0.5 mm, and 0.75 mm of gap between plate. The CP consisted of two different plate angle of 1° and 2°. All five test were compared to obtain the most optimal assessment to be used as the viscosity test for CFD simulation. A grid independence test was carried out to assess the feasibility of the model used and comparison between simulation and experimental results showed that the CFD simulation matched the experimental trends with an average percentage difference of 7.8%. The CFD simulation model and experimental work were analysed and compared at different squeegee speeds and aperture size variation. By using different value of squeegee speed, PP 0.5 mm gap provide the lowest average discrepancy between simulation and experimental results which is 5.4%. At different aperture size, all tests show a similar trend line and about the same value of average discrepancy with CP 1° and PP 0.5 mm gap gives the lowest average discrepancy at 11.6%. At smaller aperture volume, similar trends have been observed in all tests performed however PP 0.5 mm shows the lowest percentage difference than experimental values at bigger aperture volume.

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Figures

Figure 1

Solder Paste Stencil Printing Process

Spindle

Figure 2

Anton Parr Viscometer and Spindle

Figure 3

Rheology test schematic diagram

Figure 4

Mesh and Boundary conditions

Simulation

Experiment

Figure 5

Solder paste measurement using Koh Young 3D scanner and CFD simulation result for 1210 Resistor (2.54 mm × 1.016 mm)

Viscosity (Pa.s) vs Shear Rate (s^{-1})

Figure 6

Viscosity versus shear rate at different spindle test

Solder paste volume (mm^3) vs Squeegee Speed (mm/s)

Figure 7

Solder paste volume at different squeegee speed.

Solder paste volume difference (%) vs Squeegee Speed (mm/s)

Figure 8

Solder pastes volume difference in percentage at different squeegee speed

Solder paste volume (mm^3) vs Aperture Volume (mm^3)

Figure 9

Solder paste volume at different aperture size

Solder paste volume difference (%) vs Aperture Volume (mm^3)

Figure 10

Solder pastes volume difference in percentage at different aperture size

Solder paste volume difference (mm^3) vs Aperture Volume (mm^3)

Figure 11

Solder pastes volume difference at different aperture size

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