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INVESTIGATION OF PIN-IN-PASTE TECHNOLOGY BY NUMERICAL MODELLING

PHD THESIS BOOKLET

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Preliminaries

Reflow soldering is an assembly technology that is generally used for mechanical fastening and electrical joining of components to electronic circuit assemblies. In mass production, at first, the solder paste, which is a suspension containing powder of solder alloy and flux, is printed onto the surface of the assembling board through a metal mask called a stencil. The apertures of the metal mask are made in exact position, shape and volume, according to the soldering pads of the board. Then components are placed onto the board, pushing their terminals into the printed paste. The third step is preparing the joints by heating and melting – reflowing – the solder paste in conveyor type forced convection reflow ovens. Reflow soldering was developed for surface mount assembly (SMA) in the late 1960s [1]. By 1999, reflow soldering is used for the assembly of surface-mounted components in 93 per cent [2], though the through-holes (TH) components were still soldered by (selective) wave soldering at that time.

By the early part of the 2000s, a new technology, the pin-in-paste technology, started to spread, which allows the joint assembly of the surface-mounted and the through-hole components with the same process steps by reflow soldering. In pin-in-paste technology, apertures are formed in the stencil for the through-hole components also, and solder paste is pushed into the through-holes by the stencil printing. The printed circuit board is populated after both with SM and TH components, and they are soldered together in a conveyor-type oven as the last step. The advantage of this technology is the elimination of wave soldering (for the assembly of TH components), which yields cost reduction and can improve the quality and reliability of electronics products. Nevertheless, the design of the printed circuit board and the process parameter of stencil printing should carefully be optimized and controlled to provide the appropriate amount of solder paste to the through-hole components. Too much or too little solder paste can cause quality problems, like the formation of open joints, and can also lead to reliability problems, like excessive void-formation in the solder joints [3].

Since 50–60 per cent of the soldering failures can be traced back to the process of stencil printing [4], which is even more critical in pin-in-paste technology, the optimization of this process has great importance. After reviewing the relevant literature, I have found many neglects (like the exact rheological behavior of solder pastes), even lacks (like the geometry and arrangement of through-holes) in the research results of this fields. That is why I chose the topic for my thesis work to investigate the stencil printing process for pin-in-paste technology.

Open issues of the research area

The parameters affecting the stencil printing process can be categorized into four groups [5]: the rheological properties of the solder paste (which is a non-Newtonian fluid), the process parameters of the stencil printing (like printing speed), the geometrical properties (like the size of the apertures on the stencil), and the manufacturing technology of the stencil. Many research works dealt with the optimization of the stencil printing process with various methods. These methods include empirical approaches like DMAIC (Define, Measure, Analyze, Improve and Control) or Taguchi, and numerical modelling recently, as the availability of computational resources increased significantly in the last decade.

One of the critical parameters in the modelling of stencil printing is the rheological behavior of the solder paste. Glinski et al. [6] demonstrated the differences in the modelling results between using Newtonian and non-Newtonian fluid properties. They proved that non-Newtonian fluid properties shall be used to describe the viscosity of solder pastes as a function of shear rate. The Cross's viscosity model (a decaying exponential function) is used in the literature generally to address the shear-thinning (pseudo-plastic) nature of the solder paste [7–9]. Though, a plateau region is expected in the viscosity curve at low rates of shear, as demonstrated in [10], and also proved by departmental measurements. This plateau region results from the changes in the microstructure of dense suspensions under shear [11] and cannot be addressed by Cross's viscosity model. This plateau region was neglected by previous research works, which causes higher calculation errors in the modelling. In some works, the Carreau-Yasuda viscosity model [12] was used for describing the viscosity of solder pastes, but they have fit the model to measurement results where this plateau does not exist (in an initial state of the solder paste, without prior impact). Besides, the Carreau-Yasuda model can describe the viscosity of solder pastes with a higher error at high rates of shear. As a consequence, new viscosity models shall be used, which can describe the viscosity of solder pastes at a much broader range of shear rate.

The research works in the literature focus on stencil printing from the aspect of surface-mounted components. Seo and Kim [13] introduced an analysis method of solder paste flow into the stencil apertures. The drawback of their work is the usage of Newtonian fluid properties throughout their modelling. Thakur et al. created a 3D CFD-based (computational fluid dynamics) model to investigate the flow of solder pastes into the stencil apertures of surface mounted components during printing [14]. They also showed that the non-Newtonian paste properties significantly impact the yield of the stencil printing process. Namely, an increasing printing speed will increase the shear stress within the solder paste and, consequently, increase the rate of shear. Since solder pastes are shear-thinning fluids (decreasing viscosity over increasing rate of shear), an increase in the printing speed will aid the solder paste flows into the stencil apertures. It should be noted that with an increasing printing speed, the solder paste would have less time to fill up the plated holes belonging to through-hole components. Thereby, the increase in printing speed is not as straightforward in pin-in-paste technology as in Thakur's work. Rusdi et al. studied the flow of solder paste in stencil printing at different aperture sizes and squeegee speed [15]. A transient 3D CFD model was created based on the Volume of Fluid (VOF) method, and the non-Newtonian fluid properties were addressed by Cross's viscosity model [16,17]. The results error of their model could be reduced further by using a viscosity model that can address the plateau region in the viscosity curve of solder pastes.

Based on the literature review, Cross's viscosity model is used for addressing the rheological properties of solder pastes, and none of the works dealt with the hole-filling by solder paste in pin-in-paste technology; all of them investigated the process of stencil printing from the surface-mounted components point of view.

The aim and the methodology of my research

The following goals were set for my work in order to provide solutions for the problems and open issues of the research area:

- Formulating a new viscosity model, which can describe the viscosity of solder pastes at a much broader range and address the plateau region in their viscosity curve.
- Creating numerical models to test and validate complex viscosity models of solder pastes and their utilization in the modelling of stencil printing.
- Creating a 3-dimensional, transient, two-phase model for analyzing the stencil printing process in pin-in-paste technology.
- Investigating the effect of various through-hole shapes and arrangements on the hole-filling by solder paste

For the formulation of a new viscosity model, I analyzed the results of measurements (conducted by the department priorly) about the behaviour of solder pastes under different impacts; that is, how the viscosity curve changes during a sequence of analyses by a rotational rheometer using different idle times between the individual measurements. I also analyzed the Cross and Carreau-Yasuda viscosity models to reveal their strengths and weaknesses.

For the test and validation of any complex viscosity models, I created a numerical model, which describes a rotational rheometry test setup. The geometry of the model agreed to the actual dimensions of a rheometer; the diameter of the plates was 50 mm, and the gap between the stationary and rotating plates was 0.5 mm. The shear-rate control mode was modelled (like in the measurements), which means that the rate of shear (angular velocity of the rotating plane) was an input parameter in the model, and the viscosity was calculated from the shear stress on the rotating plane (1):

$$\eta = \frac{\tau \cdot h}{r \cdot \omega} \tag{1}$$

where η is the value of viscosity, τ is the calculated wall shear at a given point, r is the distance of that point from the origin (axis of rotation), h is the gap between the plates (0.5mm), and ω is the angular velocity set as an input parameter for the rotating plate. The final value of the viscosity can be determined by calculations at any middle point, which are at half of the diameter from the axis of rotation. For loading complex viscosity models into the model, I created a UDF (User Defined Function), which acquires the rate of shear from all over the fluid domain and sets the viscosity value by the specific viscosity function accordingly. Next, I prepared the numerical model of the stencil printing. The geometry of the model consisted of the printing squeegee (the angle was set according to a specific printing force of 0.3 N/mm) and the stencil as domain walls, and the solder paste as the fluid domain. The input parameters were the printing speed and the fluid properties (viscosity and density). The output parameter is the pressure gradient over the stencil, which fundamentally affects the hole-filling in pin-in-paste technology. The model was validated by setting Newtonian fluid properties and comparing the pressure gradient over the stencil to that, which can be obtained by Riemer's analytical model [18]. After the validation, complex viscosity models were utilized via the custom-UDF.

I prepared a 3-dimensional, transient, two-phase model for investigating the process of stencil printing in pin-in-paste technology. The model included the printing squeegee, the stencil, the through-hole(s) (different diameter, shape and arrangement), the solder paste as a fluid phase, and the air as a gas phase. The model was validated by comparing calculated hole-fillings (by the solder paste) to measurement results (conducted by the department priorly) for various printing speeds and hole diameters. The interaction between a set of through-holes (7 pcs.) was analyzed next for two cases: a) the through-holes were arranged parallel with the travelling direction of the printing squeegee; b) the through-holes were arranged perpendicular to it. The diameter and the z-dimension of the holes were 1.1 mm and 1.55, respectively, and they were distributed evenly from each other at distances of 2.54 mm, similarly to a lead arrangement of a through-hole serial connector. The effect of hole shape was also investigated on the hole filling. Oblong-shape through-holes were analyzed by utilizing rectangular-shaped holes in the numerical model. Five different shapes were investigated, and the linear dimensions of the holes were varied as 1.0 × 1.0, 1.0 × 1.5, 1.0 × 2, 1.0 × 2.5, 1.0 × 3.0 mm. The through-holes with different shapes were also oriented in two directions: perpendicular to and parallel with the travelling direction of the printing squeegee. The hole-fillings were investigated for various printing speeds from 20 mm/s to 120 mm/s in all cases.

New scientific results

Thesis 1: I have formulated a new viscosity model, which can describe the shear-thinning properties of solder pastes in their stabilized state, with a 20-40 percent lower error than the regularly used Cross or Carreau-Yasuda models.

Literature and prior measurements showed that the viscosity curve of solder pastes includes a plateau region at low rates of shear in the stabilized state (stable in viscosity after 5-6 preloads) of solder pastes. The Plateau region originates from the changes in the microstructure of the dense suspension under shear. To address this plateau region and to increase the accuracy of describing solder paste viscosity, I have formulated a viscosity model (2) based on the Cross and the Carreau-Yasuda models:

$$\eta_a = \beta(\eta_\infty + \frac{\eta_{0\_1} - \eta_{\infty\_1}}{\left[1+(\lambda_1\dot{\gamma})^a\right]^{\frac{1-n_1}{a}}}) + (1-\beta)(\eta_\infty + \frac{\eta_{0\_2} - \eta_{\infty\_2}}{1+(\lambda_2\dot{\gamma})^{n_2}}) \quad \text{where, e.g.,} \quad \beta(\dot{\gamma}) = \begin{Bmatrix} 1 \text{ if } & \dot{\gamma} \le \dot{\gamma}_t \\ 0 \text{ if } & \dot{\gamma} > \dot{\gamma}_t \end{Bmatrix} \qquad (2)$$

where η_a is the apparent viscosity by the model, η_{0_i} and η_{∞_i} are the asymptotic viscosity values belonging to zero and infinite rates of shear, respectively, λ_i are time constants, $\dot{\gamma}$ is the rate of shear, n_i are dimensionless exponents, and β is a weighting parameter depending on the $\dot{\gamma}_t$ threshold shear rate.

I also created a numerical model, which describes a rotational rheometry test and can test complex viscosity models via user-defined functions (UDF). Based on the results, my viscosity model can describe the viscosity curve of solder pastes with an error between 2.2–4.5% (compared to the formerly used Cross model having an error even up to 34–59%) at low shear rates, and with an error between 1.4–2.5% (compared to the Carreau-Yasuda model having an error between 2.9–3.7%) at high shear rates, in the overall shear rate range from 0.002 to 100 s^{-1}.

Related publications: L1, R1

Thesis 2: I have proven for various printing speeds that neglecting the special viscosity properties of solder pastes in their stabilized state can yield an over-estimation in the pressure distribution over the stencil surface, even by ~30%.

I created a 2D steady-state numerical model to describe the process of stencil printing, which is able to handle complex viscosity models via user-defined functions (UDF). The solder paste was treated as a homogenous liquid, and its viscosity was characterized by two models (Cross model and my model) to compare them together. The differences were analyzed for various printing speeds, from 20 to 200 mm/s. I found that the pressure difference (between the two models) is small (0–5%) near to the squeegee but increases gradually (up to 33–34%) at larger distances from the squeegee tip. Riemer's model states that the pressure on the surface of the stencil depends proportionally on the viscosity of the fluid. There are larger rates of shear within the solder paste in the proximity of the squeegee. At larger shear rates, the difference in the predicted viscosity is small between the Cross and my model, resulting in a small difference in the pressure. Contrary, at larger distances from the squeegee, the rate of shear is low, and the difference in the predicted viscosity is more significant between the Cross and my model – the plateau region in the viscosity curve of solder pastes starts playing a role. As a consequence, the pressure difference is more significant at larger distances from the squeegee.

Related publications: L2, R2

Thesis 3: I have created a 3D numerical model of the pin-in-paste printing process, which confirmed that the hole filling depends on the arrangement, orientation and shapes of the through-holes.

I created a 3D, multiphase, transient model using the Volume of Fluid method to describe the stencil printing process of the pin-in-paste technology. Through-holes with a diameter of 1.1 mm have been arranged in a parallel direction with the travelling direction of the squeegee. I found that a set of through-holes in this orientation affects the extent of filling (decrease up to ~10% in the investigated case), which should be considered during the design phase of manufacturing. The holes after each other disturb the flow field, causing a decrease in the rate of shear and in the pressure over the stencil. Since solder pastes are shear-thinning fluid, a decrease in shear rate will increase viscosity. The Hagen–Poiseuille equation states that a lower volumetric flow rate is expected by higher viscosity and/or lower pressure gradient.

Besides, I investigated the effect of the orientation and shape of oblong-type holes (I approached the oblong-type shape with rectangles in the model) on the hole-filling. I found that the filling increases significantly (10–20%) at the orientation of these holes parallel with the travelling direction of the squeegee. I found besides that the through-holes were filled almost linearly over time. Though the pressure on the solder paste increases exponentially as the squeegee travels over the through-hole. The amount of solder paste also gradually increases in the hole, introducing resistance against the filling and resulting in almost linear fill-dynamics. This implies that the hole-filling of oblong-type holes depends mainly on the duration spent by the printing squeegee and the paste over the through-holes (considering identical process and material parameters).

Related publication: L3

Applicability of the results

The new viscosity model can be utilized for more accurate modelling of the stencil printing process, enhancing the optimization of this process. Especially at small and medium enterprises, where the cost-demanding empirical (trial-and-error) optimization methods are not feasible. Addressing the effect of dynamic parameters, e.g., the stencil separation speed in the numerical investigation, can also be carried out more precisely by taking the recommendation about the use of complex viscosity models of solder pastes.

The variations in the hole-filling (shown in Thesis 3) can be considered either in the design phase of the electronics products or the manufacturing processes. Through-hole connectors should be oriented perpendicular to the travelling direction of the printing squeegee to minimize the interaction between the holes and the variation in hole-filling. If this is not feasible, and circular lead connectors are oriented parallel with the squeegee movement, providing additional solder paste to the last holes might be required, e.g. by utilizing pre-form (pre-shaped, fluxless) solders. The soldering failures in pin-in-paste technology can be reduced by these early design-phase considerations, and the first-pass yield of electronics soldering technologies can be enhanced. The early phase of product design can be aided by the following recommended procedure: a) measure the rheological curve of solder pastes in their stabilized state down to at least the rate of shear of 0.01; b) utilize an appropriate squeegee attack angle based on its overhang size, unloaded angle, and the specific printing force; c) fit a complex material model to the viscosity curve over the whole range of shear rate; d) include the geometry of the most critical components, .e.g., fine-pitch integrated circuits or through-holes for pin-in-paste technology; e) if pin-in-paste technology applies, perform a calculation over the range of printing speeds to find the optimal one for a specific solder paste hole-filling.

List of Publications

Publications related to the thesis claims

International, peer-reviewed journal papers

[L1] **T. Al-Ma'aiteh,** O. Krammer, "Non-Newtonian Numerical Modelling of Solder Paste Viscosity Measurement", *Soldering & Surface Mount Technology*, Vol. 31, Issue 3, 2019, pp. 176-180.

[L2] O. Krammer, **Tareq I. Al-Ma'aiteh**, B. Illes, D. Bušek, K. Dušek, "Numerical investigation on the effect of solder paste rheological behaviour and printing speed on stencil printing", *Soldering & Surface Mount Technology*, Vol. 32, Issue 4, 2020, pp. 219-223.

[L3] **T. Al-Ma'aiteh**, O. Krammer, B. Illés, "Transient numerical modelling of the pin-in-paste technology", *Applied Sciences*, Vol. 11, Issue 10, 2021, ID: 4670.

Papers published in referenced proceedings of international conferences

[R1] **T. Al-Ma'aiteh**, O. Krammer, "Particle Level Modelling of Solder Pastes Rheological Behaviour in Viscosity Measurement", *Proceedings of 42th IEEE-ISSE conference*, Wroclaw, Poland, 2019. pp. 1-6.

[R2] O. Krammer**, T. Al-Ma'aiteh**, P. Martinek, "Investigating the Effect of Viscosity Models on the Stencil Printing by Numerical Modelling", *Proceedings of 42th IEEE-ISSE conference*, Wroclaw, Poland, 2019. pp. 1-6

Other publications

International, peer-reviewed journal papers

[L4] **T. Al-Ma'aiteh**, O. Krammer, "Thermoelectric Generators Simulation in Aircraft Applications", *Int. J. Sustainable Aviation,* Vol. 5, No. 4, 2019, pp. 313-323.

Papers published in referenced proceedings of international conferences

[R3] O. Krammer, **T. Al-Ma'aiteh**, P. Martinek, A. Géczy, "Establishing a Machine-learning Based Framework for Optimising Electronics Assembly", *Proceedings of 44th IEEE-ISSE conference*, Germany (online), 2021, pp. 1-5.

[R4] O. Krammer, **T. Al-Ma'aiteh**, P. Martinek, K. Anda, N. Balogh, "Predicting the Transfer Efficiency of Stencil Printing by Machine Learning Technique", *Proceedings of 43th IEEE-ISSE conference*, Slovakia (online), 2020, pp. 1-6.

[R5] M. Alaya**,** L. Gál, T. Hurtony, B. Medgyes, D. Straubinger, **T. Al-Ma'aiteh**, B. Illés, A. Géczy, "Wetting of different lead free solder alloys during vapour phase soldering", *Proceedings of 42th IEEE-ISSE conference*, Wroclaw, Poland, 2019. pp. 1-6.

Papers published in proceedings of international conferences

[K1] **T. Al-Ma'aiteh**, U. Kale, "Thermoelectric Unit Modelling in Aircraft Applications" *International Symposium on Electric Aviation And Autonomous Systems (ISEAS-2019)*, Budapest, Hungary, 2019. pp. 63-66.

References

[1] K. W. Gurnett, *Surface Mount Handbook*. Oxford: Butterworth-Heineman, 1999.

[2] S. Houson, "Surface mount technology market forecasting", *J. Ind. Technol.*, vol. 17, no. 1, p. 2, 2001.

[3] R. Kay and M. Desmulliez, "A review of stencil printing for microelectronic packaging", *Soldering and Surface Mount Technology*, vol. 24, no. 1, pp. 38–50, 2012.

[4] T. N. Tsai, "Modeling and optimization of stencil printing operations: A comparison study", *Comput. Ind. Eng.*, vol. 54, no. 3, pp. 374–389, 2008.

[5] L. Haslehurst and N. N. Ekere, "Parameter interactions in stencil printing of solder pastes", *J. Electron. Manuf.*, vol. 6, no. 4, pp. 307–316, 1996.

[6] G. P. Glinski, C. Bailey, and K. A. Pericleous, "A non-Newtonian computational fluid dynamics study of the stencil printing process", *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 215, no. 4, pp. 437–446, 2001.

[7] R. Durairaj, G. J. Jackson, N. N. Ekere, G. Glinski, and C. Bailey, "Correlation of solder paste rheology with computational simulations of the stencil printing process", *Solder. Surf. Mt. Technol.*, vol. 14, no. 1, pp. 11–17, 2002.

[8] R. Durairaj, T. A. Nguty, and N. N. Ekere, "Critical factors affecting paste flow during the stencil printing of solder paste", *Solder. Surf. Mt. Technol.*, vol. 13, no. 2, pp. 30–34, 2001.

[9] T. A. Nguty and N. N. Ekere, "The rheological properties of solder and solar pastes and the effect on stencil printing", *Rheol. Acta*, vol. 39, no. 6, pp. 607–612, 2000.

[10] C. M. Ionescu, I. R. Birs, D. Copot, C. I. Muresan, and R. Caponetto, "Mathematical modelling with experimental validation of viscoelastic properties in non-Newtonian fluids", *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences*, vol. 378, no. 2172, 20190284, 2020.

[11] J. J. Stickel and R. L. Powell, "Fluid Mechanics and Rheology of Dense Suspensions", *Annu. Rev. Fluid Mech*, vol. 37, pp. 129–178, 2005.

[12] J. Boyd, J. M. Buick, "Analysis of the Casson and Carreau-Yasuda non-Newtonian blood models in steady and oscillatory flows using the lattice Boltzmann method", *Phys. Fluids*, vol. 19, no. 9, 093103, 2007.

[13] W. S. Seo, J. B. Kim, "Filling analyses of solder paste in the stencil printing process and its application to process design", *Solder. Surf. Mt. Tech.*, vol. 25, no. 3, pp. 145–154, 2013.

[14] V. Thakur, S. Mallik, V. Vuppala, "CFD Simulation of Solder Paste Flow and Deformation Behaviours during Stencil Printing Process", *Int. J. Recent Adv. Mech. Eng.*, vol. 4, no. 1, pp. 1–13, 2015.

[15] M. S. Rusdi, M. Z. Abdullah, M. S. Abdul Aziz, M. K. Abdullah@Harun, S. Chellvarajoo, A. Husin, P. Rethinasamy, S. Veerasamy, "Multiphase Flow in Solder Paste Stencil Printing Process using CFD approach", *J. Adv. Res. Fluid Mech. T. Sci.*, vol. 46, no. 1, pp. 147–152, 2020.

[16] M. S. Rusdi, M. Z. Abdullah, M. S. Abdul Aziz, M. K. Abdullah, M. H. Hafiz Ishak, Y. Kok Hwa, P. Rethinasamy, S. Veerasamy, D. G. Santhanasamy, "SAC105 Stencil Printing Process using Cross Viscosity Model", *J. Adv. Res. Fluid Mech. T. Sci.*, vol. 54, no. 1, pp. 70–77, 2020.

[17] M. S. Rusdi, M. Z. Abdullah, M. H. H. Ishak, M. S. Abdul Aziz, M. K. Abdullah, P. Rethinasamy, A. Jalar, "Three-dimensional CFD simulation of the stencil printing performance of solder paste", *Int. J. Adv. Manuf. Tech.*, vol. 108, pp. 3351–3359, 2020.

[18] D. Riemer, "Analytical engineering model of thescreen printing process: Part I.", *Solid State Technol.*, August, pp. 107–111. 1988.

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