

Correlation between jamming and skipping during solder paste printing

S.R. Hillman and S.H. Mannan

Department of Mechanical Engineering, King's College London, London, UK

R. Durairaj, A. Seman and N.N. Ekere

Medway School of Engineering, University of Greenwich at Medway, Kent, UK, and

M. Dusek and C. Hunt

CMMT, National Physical Laboratory, Middlesex, UK

Abstract

Purpose – To investigate how jamming of particles in a solder paste varies as a function of the gap through which the particles flow, and to correlate this with skipping defects during the printing process.

Design/methodology/approach – Solder pastes with particle sizes of types 2, 3, 4 and 5 were sheared between the parallel plates of a rheometer. Jamming events that cause the solder particles to be forced against each other were detected by monitoring the electrical current flowing between the plates under a bias of 1.0 V or less. Solder paste printing trials were conducted with the same pastes, and solder paste skipping monitored.

Findings – Jamming was detected when the ratio of plate gap to largest particle diameter is reduced to a value between 3.8 and 5.0. Decreasing the gap further results in increased jamming. A strong correlation between levels of skipping and jamming was found.

Research limitations/implications – More extensive printing trials are required before rheometric jamming detection can be used to predict printing performance.

Practical implications – The common rule of thumb used in solder paste printing that the aperture width should be no smaller than 4-5 particle diameters is justified.

Originality/value – This paper presents a new technique for detecting jamming events which are too brief to be detected using normal rheometric techniques, but which have long been thought to be responsible for stochastic skipping defects during printing. Evidence supporting the link between jamming and this type of defect is presented.

Keywords Solder, Soldering, Zero defects, Electrical conductivity

Paper type Research paper

Introduction

Solder pastes for electronics assembly consist of metal alloy particles (typically Sn-Pb or Sn-Ag-Cu alloys) suspended in a non-Newtonian fluid at a volume fraction close to 50 per cent. The paste is usually deposited onto a printed circuit board (PCB) or other substrate through a stencil which contains narrow apertures. Electronics miniaturization, and new processes such as “flip chip bumping” have pushed the requirements for fine pitch solder paste printing, and printability of pastes through 0.03 mm wide apertures has been reported (Manassis *et al.*, 2004). Smaller particles facilitate printing through these small apertures, but exacerbate defects in the subsequent reflow process such as solder balling due to the increased surface area of the solder particles. Pastes are therefore carefully chosen to contain the largest particles that can be printed through the

stencil apertures without exhibiting skipping. Here, skipping is defined as incomplete release of the paste from the aperture, as shown in Figure 1.

Solder paste printing requires careful set-up of the printing parameters to minimize printing defects. These defects include skipping, and bridging (when adjacent paste deposits slump and merge together). Skipping results in weak joints or even open-circuits after reflow and is costly to detect and rework. However, even when the basic printer settings have been optimised, the stochastic nature of the printing process results in the occasional skipped pad, often attributed to a localized jamming event in a particular aperture; evidence supporting this hypothesis is presented in this paper.

A number of studies (Bao *et al.*, 1998; Nguty *et al.*, 2001), have attempted to predict printing performance in terms of the paste rheology and visco-elastic performance. This involves finding constitutive equations for the paste, followed by modelling of paste behaviour in printing geometries. The technique we describe in this paper bypasses these steps by directly measuring the propensity of the paste to jam in narrow apertures. This technique consists of shearing the paste between the parallel plates of a

The Emerald Research Register for this journal is available at www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at www.emeraldinsight.com/0954-0911.htm

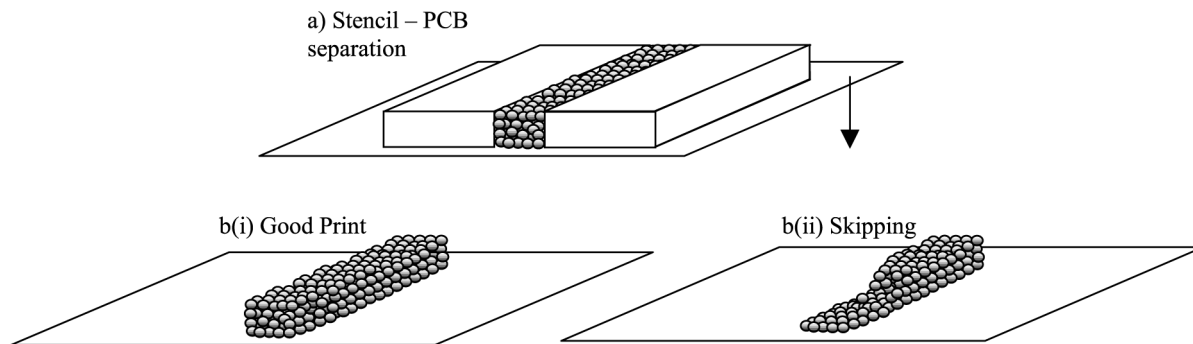


Soldering & Surface Mount Technology
17/4 (2005) 17–26
© Emerald Group Publishing Limited [ISSN 0954-0911]
[DOI 10.1108/09540910510630395]

Received: 5 January 2005

Revised: 19 July 2005

Accepted: 20 July 2005

Figure 1 Skipping defect during stencil printing

rheometer across which a small voltage difference is applied. Jamming events cause large mechanical forces between the particles which results in the insulating oxide on the particles to be broken through. These events are then detected by measuring the current flowing between the plates. Because the technique can detect a single jamming event, even when the paste as a whole is flowing smoothly, it is ideally suited for predicting the low probability jamming events which hinder efforts to reach six sigma quality. It should be emphasized that these low probability events are distinct from skipping caused by excessive adhesion to the aperture walls due to poor stencil design (Mannan *et al.*, 1993; Rodriguez and Baldwin, 1999). For the latter defect, skipping would occur irrespective of particle size and the general rule of thumb to ensure that this type of skipping does not occur is that the ratio of aperture width to stencil thickness is 1.3–1.5 or greater.

Recent studies have shown that inter-particle contacts play a significant role as the volume fraction of particles increases (Wilson and Davis, 2002; Kolli *et al.*, 2002; Lootens *et al.*, 2003). However, the effects of inter-particle contacts become even more pronounced when the boundary walls are separated by a small gap due to the excluded volume effect at the walls. This effect is caused by the fact that the centres of spheres cannot be located at a distance less than one sphere radius from the walls, causing the local volume fraction to decrease near the boundaries, and increase further from them. This effect, together with the fact that, as the gap narrows, it takes fewer particles to bridge the gap, would suggest that jamming should be a steep function of the gap separating the plates, as has been observed in our experiments. In particular, we observe a step change in jamming when the gap is 4–5 times larger than the largest particles in the paste, in agreement with an analysis of particle packing in apertures which also sees a transition at around 4–5 particle diameters (He *et al.*, 2003). It should be noted that during solder paste printing, a standard rule of thumb for defect free printing is to keep the aperture width greater than 4–5 particle diameters (www.christopherinternational.com/soldering%20materials%20overview%202.pdf).

The metal particles in a solder paste are in contact with each other, as their volume fraction exceeds the percolation threshold. Although AC current can flow through the paste, DC current is normally blocked as each particle is surrounded by an insulating oxide layer with a thickness of ~ 2 nm (Kuhmann *et al.*, 1998). However, if the particles are jammed together, then mechanical abrasion of the insulating layer results in true metal-to-metal contact occurring between particles and current may then flow

through the paste. Therefore, by monitoring the current that flows through the paste, the frequency, extent and duration of jamming events can be recorded, as described in the next section. The current experimental set-up improves on a previous attempt (Mannan *et al.*, 1999) by using higher sampling rates for monitoring the current flowing through the paste and also by using improved rheometer plates. The previous study also considered only a single paste size distribution, whereas we have now examined four distributions.

We have also conducted printing trials using the same pastes, and apertures with the same widths as the gaps in the jamming experiments in order to see whether the jamming events we observe are correlated with skipping defects. Although there is strong correlation between the two, more extensive printing trials are required to fully understand the connection between stochastic skipping defects and jamming observed during paste shearing.

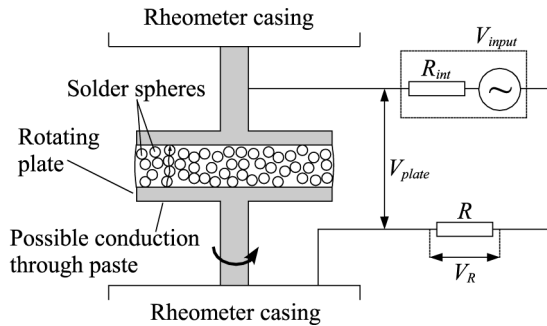
Experimental technique for monitoring jamming

The solder pastes were sheared in a TA instruments ARES rheometer using 8.0 mm diameter parallel rheometric plates. The small plate diameter was essential to prevent particle crushing during gap setting (the lowering of the top plate onto the bottom plate to reach a pre-determined gap height), which tended to immediately remove the oxide layers on the particles. The plates were also electroplated with Rhodium to provide good electrical contact and a hard wearing surface.

A function generator with internal resistance (R_{int}) of 50 Ω was used to provide a sinusoidal voltage across the plates with a frequency of either 1.0 Hz or 5.0 kHz. The high frequency measurements were used to provide further information on the oxide layers present, but were not high enough to allow a significant capacitance-based current to flow between the plates. An amplitude of 2 V peak to peak was used, as this allowed high resolution recording and did not appear to cause dielectric breakdown in the paste, as results with amplitudes as small as 0.1 V were similar to those taken at higher voltages.

The voltage recording system was PC-based, using a simultaneous sample-and-hold 14 bit data acquisition card and a PCI interface. Sampling rates up to 1 MHz per channel were used, resulting in large amounts of data (typically, recording two channels at 1 MHz each for 10 min produces a 2.4 GB binary file). Since conduction events lasting for less than 0.2 ms have not been observed, the sampling rates used are deemed to be satisfactory. Figure 2 shows the basic experimental set-up.

Figure 2 Diagram of experimental set-up to detect conduction events related to jamming



Differential voltages across the rheometer plates (V_{plate}) and across the $10\ \Omega$ resistor R (V_R) were recorded. The paste resistance, R_{paste} , is given by

$$R_{paste} = V_{plate}R/V_R \quad (1)$$

Noise levels were kept to a minimum using shielded cabling where possible. Occasional high voltage noise spikes were detected but typically the noise level was very low compared to the input voltage (V_{input}). Noise spikes detected in control experiments, which were run without paste in the gap between plates, showed characteristics which easily allowed them to be distinguished from genuine conduction events. Figure 3 shows a typical conduction event obtained using this set-up and using an input voltage amplitude and frequency of 2V peak to peak, at 1Hz, and using a sampling rate of 1 MHz. Three distinct conduction events are visible.

Experiments were typically run for 600s on a given paste sample, as it was noticed that the viscosity of the paste tended to decrease with time, and hence that either the rheological properties of the paste were changing, e.g. due to settling, or that paste was being lost from the gap. Figure 4 shows the recorded viscosity as a function of time for three repeated experiments for the same paste, some of which exhibited conduction, and some of which did not. No correlation between instantaneous viscosity and conduction events were found, indicating that the jamming events do not affect the flow of paste as a whole, but are localised.

From Figure 4 it is tempting to conclude that the sharper drop off in viscosity of the non-conducting repeat is connected to the fact that it did not conduct, but counter

Figure 3 Typical plot of V_R during conduction

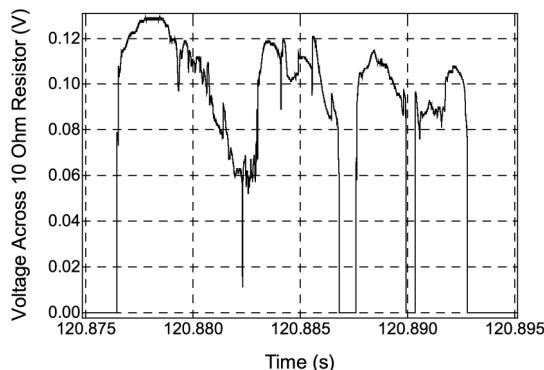
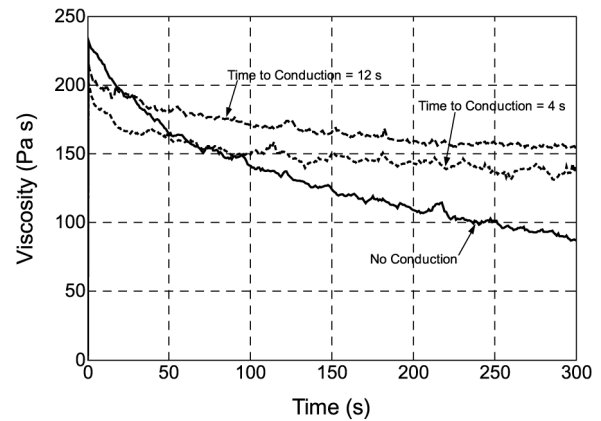


Figure 4 Viscosity plots for repeated experiments on type four paste, gap = 0.15 mm, shear rate = $10\ s^{-1}$



examples to this correlation were also seen, as shown in Figure 5. This feature of nominally identical repeats producing different results was seen throughout the experiments, so several repeats of the experiments (usually three) were used to try to discern the trends. The scatter in the results is not unexpected since jamming is a stochastic process.

Results for jamming in solder pastes

The solder pastes that were tested differed only in particle size distribution, and all contained the same weight fraction of particles (89.5 ± 1 wt per cent). The solder alloy was 63Sn37Pb. The flux used was a no-clean formulation, and the particle size distributions are listed in Table I, together with the ratios of gap to particle diameter at which jamming was first detected. The nominal size distribution limits are those given by the manufacturer to contain at least 80 per cent of the particles in the paste. The measured limits (100 per cent of particles in the paste) and average diameters were found after separating the particles from the flux and examination under a scanning electron microscope.

The parameter that was chosen to represent the severity of jamming in a given experiment was the time lapse from the moment the paste is first sheared until the first conduction

Figure 5 Viscosity/time plots for repeated experiments on type 2 paste, gap = 0.3 mm, shear rate = $5\ s^{-1}$ showing no conduction for highest level viscosity curve

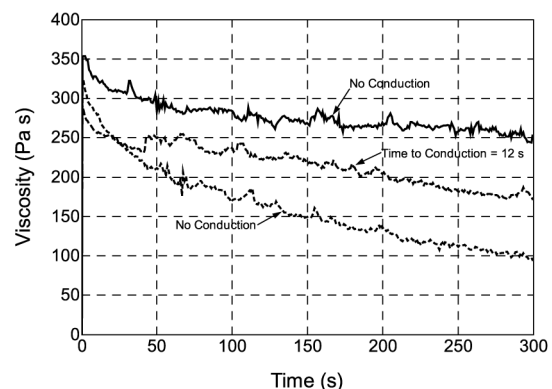


Table 1 Solder particle size distributions and the ratios of gap to particle diameter at which jamming was first detected

Paste type	Nominal size distribution (μm);		Standard deviation of particle size/average particle size (%)	Gap/average particle size below which jamming occurs	Gap/max particle size below which jamming occurs	
	Limits	Averages				
2	45-75	6-63	47	18	5.1	3.8
3	25-45	9-47	33	17	5.5	3.8
4	20-38	8-47	25	33	8.0	4.1
5	15-30	3-28	21	21	6.6	5.0

event occurs. This parameter agrees well with other parameters such as the maximum current levels observed during the experiment, and frequency of events, while being simpler to compute. The conduction events were distributed randomly throughout the experiments. Figures 6-9 show the time to conduction for each of the pastes tested, as a function of the gap between the plates. The shear rate for each of these graphs is 10 s^{-1} , and the experiment ends after 600 s, so data points plotted at 600 s indicate that no conduction event was recorded for that particular repeat. The results for each of the three repeats are plotted using separate symbols (diamond, square and triangle).

These graphs show a degree of scatter, but also show clearly discernable trends; as the gap between the plates increases, jamming decreases. Also, as the particle size decreases for a given gap, jamming decreases. Before attempting to correlate the results with skipping defect rates during printing, we have to consider the effect of shear rate on the results. Figures 10-12 show the effect of varying shear rates for each type of paste at a fixed gap of 0.16 mm. For the type 5 paste, no conduction events were observed at any shear rate up to 30 s^{-1} . The total shear in Figures 10-12 is maintained constant at 6,000, so that the duration of each repeat is inversely proportional to shear rate (6,000 s at a shear rate of 1 s^{-1} , etc.).

Although it is clear that increasing shear rate causes more jamming, we note that the results do not appear to be highly sensitive to shear rate. The stencil-substrate separation speed that was used for the printing trials was 0.2 mm/s. For a 0.16 mm wide aperture, if we assume that the solder at the stencil wall has a downward velocity of zero, while the paste at the centre of the aperture moves at the velocity of the substrate (standard boundary conditions for Newtonian fluids), then we expect shear rates in the paste of the order of $0.2/(0.16/2) = 2.5\text{ s}^{-1}$. The shear rate in Figures 3-8 was

10 s^{-1} , and so we would expect to be able to draw predictions about skipping in our printing trials from these graphs.

Printing trial results

Two separate printing trials took place, separated by approximately 3 months. In the first, a DEK 260 printer was used, using a 150 mm long, 94-97 Shore hardness squeegee blade (squeegee angle = 60°) with a $150\text{ }\mu\text{m}$ thick laser cut stencil. The squeegee speed and down-force on the squeegee were set at 20 mm/s and 5.2 kg, respectively, for all pastes. The pastes were printed onto 1.0 mm thick Cu plated PCBs. Paste volumes were recorded using a ASC international VisionMaster[®] laser scanning system, for a series of apertures with widths of 75, 125 and $200\text{ }\mu\text{m}$. However, because the aspect ratio of the 75 and $125\text{ }\mu\text{m}$ wide apertures was smaller than 1.3, skipping was widespread. Skipping was found to depend on the location of the pad on the stencil, and on the orientation of the pad, suggesting that skipping was being caused by factors other than jamming of the paste (e.g. uneven squeegee blade, or warped PCB). Figures 13 and 14 show the results of these trials for 0.2 mm wide apertures. Perpendicular apertures are defined as those oriented perpendicular to the squeegee direction of motion (i.e. parallel to the squeegee blade), while parallel apertures are aligned along the squeegee direction of motion.

A second set of printing trials was then performed using the same pastes on a DEK 265 printer, and using a different stencil. The squeegee type was the same, but the stencil was $75\text{ }\mu\text{m}$ thick and laser cut. The squeegee speed and down-force on the squeegee were set at 25 mm/s and 3 kg, respectively, for all pastes. The pastes were printed onto 3 mm thick Cu plates. Skipping was observed by manual observation of printed pads through an optical microscope and was classed as either marginal, or bad, depending on the volume of the printed deposit. The stencil apertures had widths of 160, 155, 150, 145 and $140\text{ }\mu\text{m}$. However, it was subsequently observed that the $150\text{ }\mu\text{m}$ apertures contained cured adhesive from previous experiments, and were therefore discarded in the analysis. Figures 15-18 show the skipping rates for paste types 2-5 and aperture widths $140\text{--}160\text{ }\mu\text{m}$. A total of 120 apertures were examined for each combination of paste type and aperture width.

Comparing the skipping defect rates for the different aperture widths it is evident that wider apertures did not always result in lower skipping levels. This could be an indication that again, location of the apertures on the stencil played a significant role in determining defect levels, and

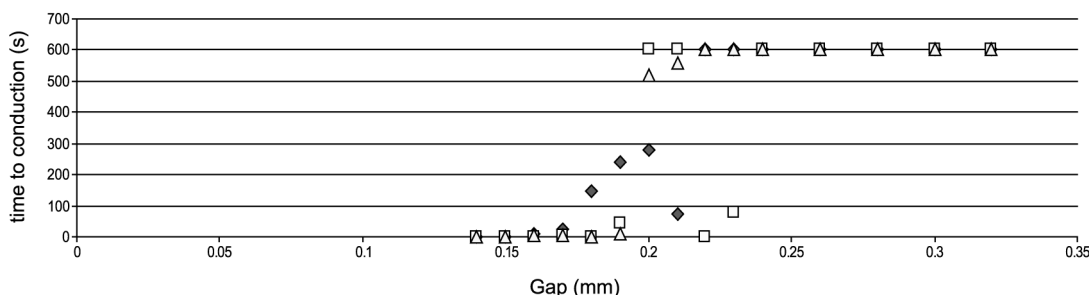
Figure 6 Time to first conduction event versus gap for type 2 paste

Figure 7 Time to first conduction event versus gap for type 3 paste

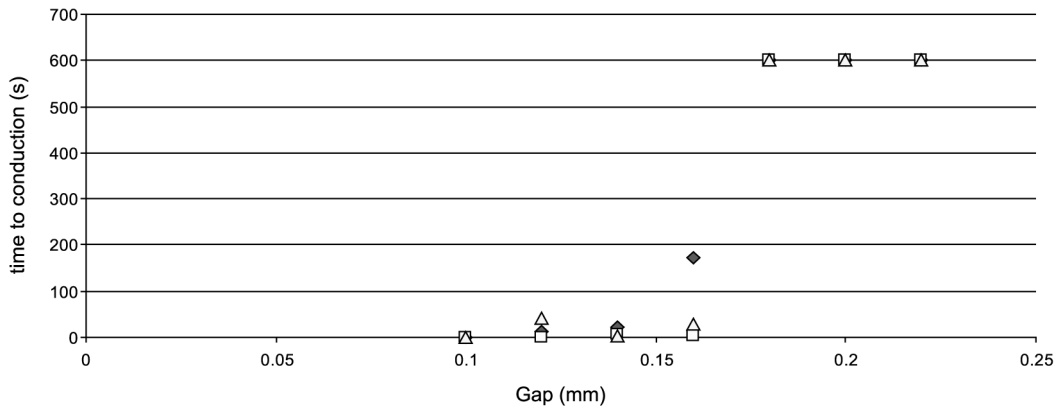


Figure 8 Time to first conduction event versus gap for type 4 paste

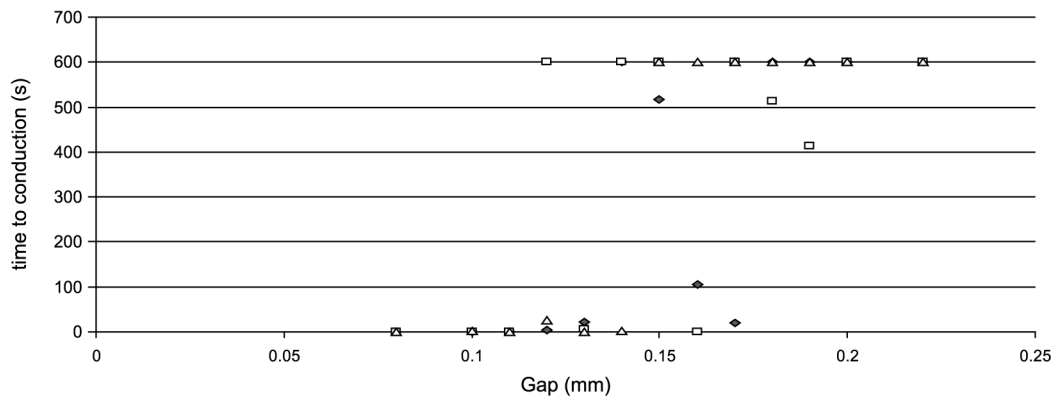


Figure 10 Accumulated shear until first conduction event versus shear rate for type 2 paste

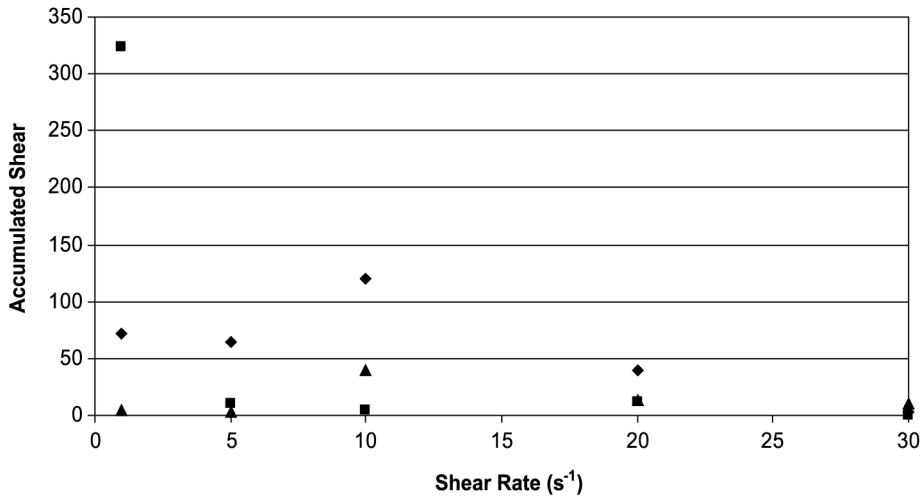


Figure 11 Accumulated shear until first conduction event versus shear rate for type 3 paste

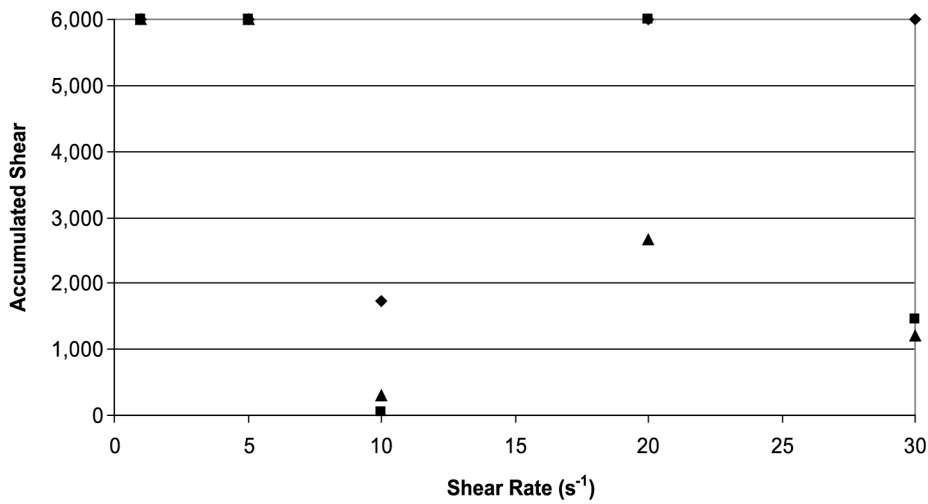


Figure 12 Accumulated shear until first conduction event versus shear rate for type 4 paste

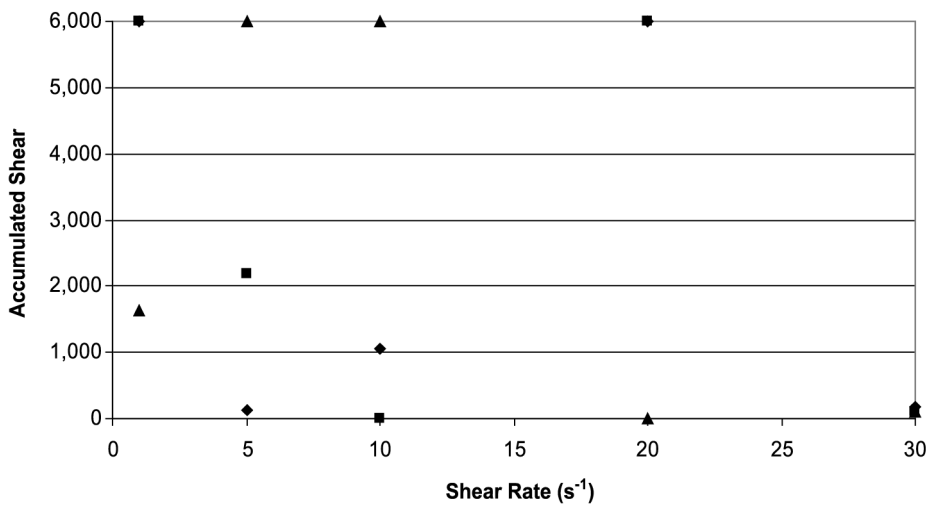


Figure 13 Percentage of skipped perpendicular apertures (out of 18) versus paste type. First set of printing trials

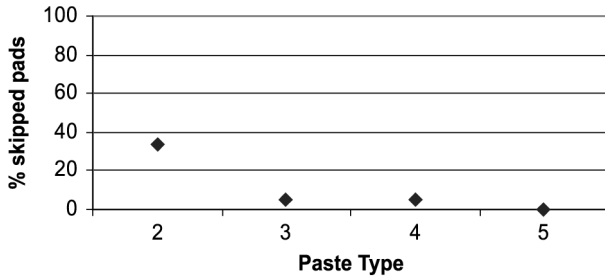
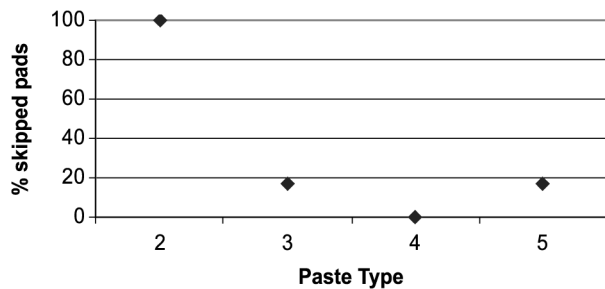


Figure 14 Percentage of skipped parallel apertures (out of 12) versus paste type. First set of printing trials



shear rate profile across the aperture during separation of the stencil and substrate is, however, unknown, and based on assumptions of symmetry must be zero at the centre of the aperture, so an exact analogy between the two processes is difficult to justify. However, the fact that in both processes, relative movement between particles may result in jamming, indicates that there should be some correlation between the results. Indeed, a cursory examination of Figures 6-9 (jamming) and Figures 13-18 (skipping) certainly shows that decreasing particle size results in the same trends in both jamming and skipping. Moreover, the skipping “rule of thumb” that apertures should be 4-5 times larger than the maximum particle size correlates extremely well with the values seen in Table I. However, the real test of the usefulness of the jamming detection technique, is whether we could

predict the characteristics of Figures 13-18 from Figures 6-9. It will, however, never be possible to predict skipping only from jamming results, as other factors, such as stencil wall roughness and the angle of the aperture walls (taper) will also be important. Another complicating factor is that if we had chosen a different shear rate for Figures 6-9, or run the experiments for longer than 600 s, the results would have been expected to shift slightly.

Figure 6 shows that the type 2 paste should experience severe jamming in apertures less than 0.2mm wide, and indeed, skipping defects are close to 100 per cent for this paste in Figures 15-18. At 0.2mm, there are also significant numbers of skipped pads, as shown in Figures 13-14, and this correlates with the mixed results seen in Figure 6 at this gap setting. For the type 3 paste, from Figure 7, we would expect defect free printing down to 0.18mm, but not down to 0.16mm, and indeed defect levels at 0.2mm for type 3 pastes are seen to be similar to those of types 4 and 5 (Figures 13-14), indicating that jamming is no longer a cause of skipping. Skipping is, however, significantly higher for the type 3 paste for apertures 0.16mm or smaller, as seen in Figures 15-18.

Comparing Figure 7 and 8 at 0.2mm, we would expect to see little difference in the printing performance of paste type 3 and 4 at 0.2mm width, and both should print well. However, for gaps in the range 0.16-0.14mm, we see that the type 4 paste exhibits significantly less jamming than the type 3 paste, and Figures 15-18 confirm that skipping rates are also significantly smaller. Note, however, that Figure 8 shows that there is some jamming for the type 4 paste in the 0.14-0.16mm range, and hence that we would expect to see non-zero skipping rates if sufficient numbers of apertures are checked. Finally, Figure 9 shows that type 5 paste should exhibit no defects down to 0.14mm aperture width, and Figures 15-18 do show low (but non-zero) rates of skipping for this paste down to 0.14mm. However, we would not expect to see such low levels if we decreased the aperture width down to 0.12mm, as jamming is detected at that gap.

Conclusions

A new experimental technique used to detect jamming in a dense suspension by electrical methods has been presented. The results show a large degree of scatter, as was expected for a stochastic process. However, the results were not completely

Figure 15 Percentage of badly skipped apertures versus paste type. Second set of printing trials

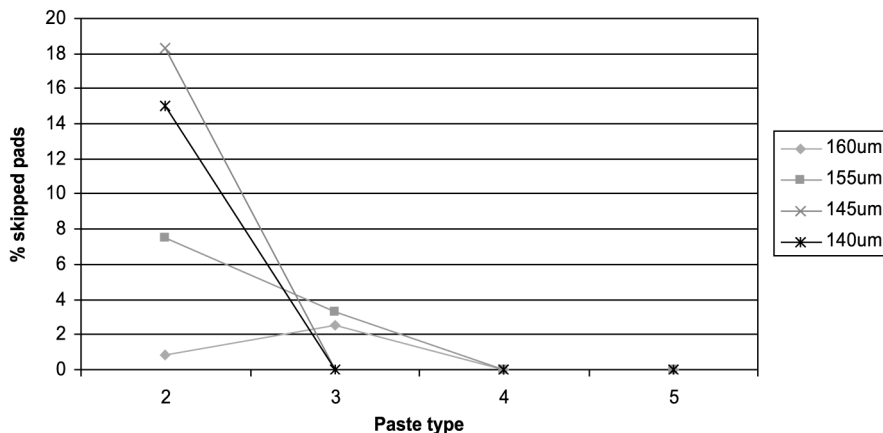


Figure 16 Percentage of skipped apertures (bad + marginal) versus paste type. Second set of printing trials

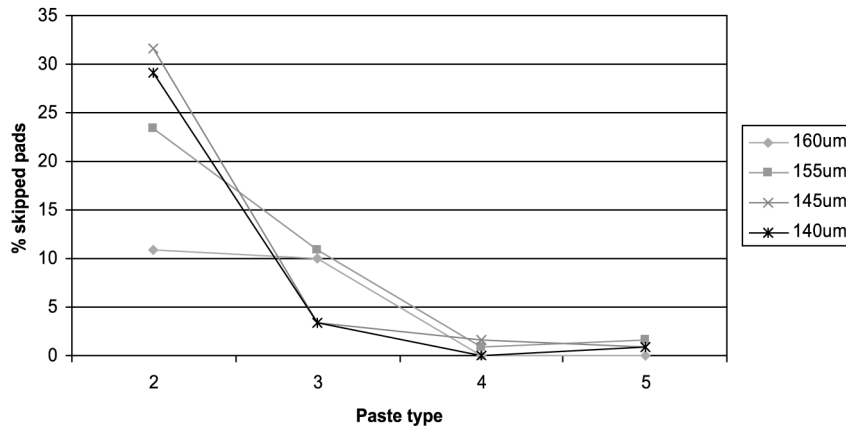


Figure 17 Percentage of badly skipped apertures versus paste type. Second set of printing trials

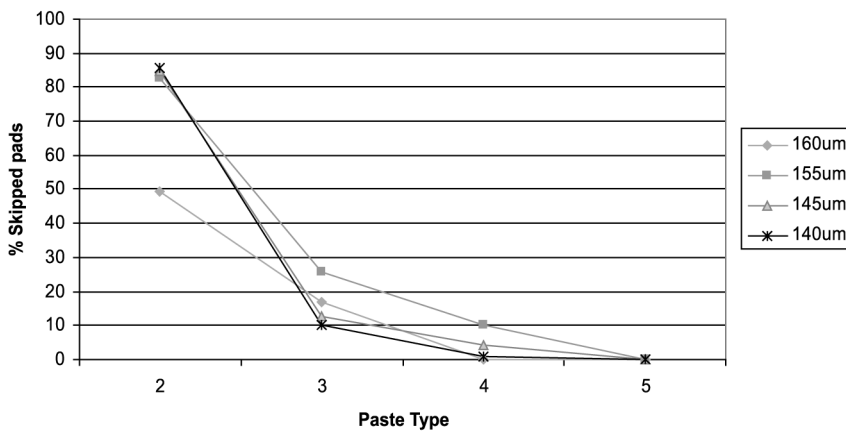
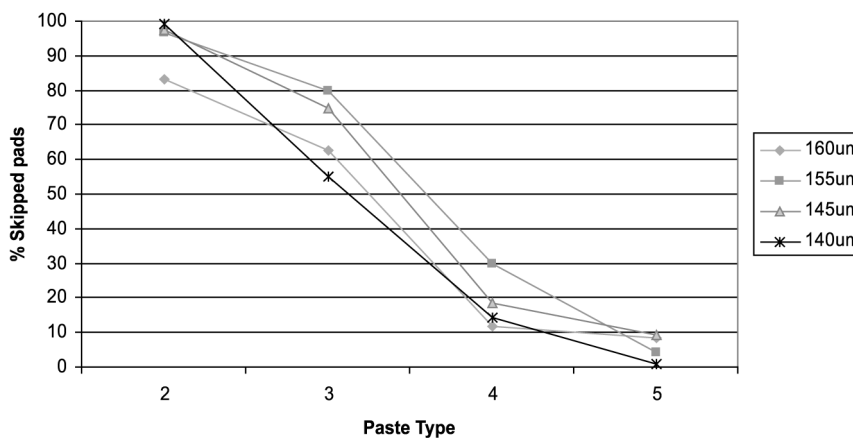


Figure 18 Percentage of skipped apertures (bad + marginal) versus paste type. Second set of trials



random, and conclusions could be drawn from the results. For example, the rule of thumb stating that the minimum aperture width should be more than 4-5 times the largest particle diameter has been correlated to the occurrence of jamming for all paste types investigated.

We have shown that there is a very strong correlation between skipping defect levels and jamming detected during

solder paste shearing at gaps corresponding to the aperture width. In particular, where jamming is observed, we see significantly higher levels of skipping. However, we have not been able to prove that an absence of jamming should result in zero levels of skipping, because skipping in our printing trials is caused by additional factors beyond jamming of particles inside the apertures. We speculate that if these other

sources of skipping defects were to be removed, the correlation between jamming and skipping would be much stronger. In this case, the jamming tests could quickly reveal the ultimate defect-free printing capabilities of a given paste, without the need for extensive printing trials.

We also note that the relative insensitivity of jamming to shear rate may be the reason that the stencil – substrate separation speed is not a major factor in controlling skipping defects (Ekere *et al.*, 1993). Note, however, recent results indicating that it could be more significant for lead free pastes (Ashmore, 2004), possibly related to differences in particle surface roughness.

References

- Ashmore, C. (2004), "Mass imaging performance with lead-free solder", *Surface Mount Technology*, Vol. 18 No. 11, pp. 32-7.
- Bao, X.H., Lee, N.C., Raj, R.B., Rangan, K.P. and Maria, A. (1998), "Engineering solder paste performance through controlled stress rheology analysis", *Soldering & Surface Mount Technology*, Vol. 10 No. 2, pp. 26-35.
- Ekere, N.N., Ismail, I., Lo, E.K. and Mannan, S.H. (1993), "Experimental study of stencil-substrate separation speed in on-contact solder paste printing for reflow soldering", *Journal of Electronics Manufacturing*, Vol. 3 No. 1, pp. 25-9.
- He, D., Ekere, N.N., Salam, B., Rajkumar, D. and Jackson, G. (2003), "Monte Carlo study of solder paste microstructure and ultra-fine-pitch stencil printing", *Journal of Materials Science – Materials in Electronics*, Vol. 14 No. 8, pp. 501-6.
- Kolli, V.G., Pollauf, E.J. and Gadala-Maria, F. (2002), "Transient normal stress response in a concentrated suspension of spherical particles", *Journal of Rheology*, Vol. 46 No. 1, pp. 321-34.
- Kuhmann, J.F., Maly, K., Preuss, A., Adolphi, B., Drescher, K., Wirth, T., Oesterle, W., Fanciulli, M. and Weyer, G. (1998), "Oxidation and reduction of liquid SnPb (60/40) under ambient and vacuum conditions", *Journal of Electrochemical Society*, Vol. 145 No. 6, pp. 2138-42.
- Lootens, D., Van Damme, H. and Hebraud, P. (2003), "Giant stress fluctuations at the jamming transition", *Physical Review Letters*, Vol. 90 No. 17, art. no. 178301.
- Mannan, S.H., Ekere, N.N., Lo, E.K. and Ismail, I. (1993), "Predicting scooping and skipping in solder paste printing for reflow soldering of SMT devices", *Soldering and Surface Mount Technology*, Vol. 15 No. 1, pp. 14-17.
- Mannan, S.H., Ekere, N.N., Lo, E.K. and Ismail, I. (1994), "Squeegee deformation study in the stencil printing of solder pastes", *IEEE Transactions on Comparative, Hybrids and Manufacturing Technology – Part A*, Vol. 17 No. 3, pp. 470-6.
- Mannan, S.H., Hutt, D.A. and Whalley, D.C. (1999), "Electrical method of monitoring percolation and abrasion of conducting spheres due to shear flow of a dense suspension in a narrow gap", *Applied Physics Letters*, Vol. 75 No. 6, pp. 871-2.
- Manassis, D., Patzelt, R., Ostmann, A., Aschenbrenner, R. and Reichl, H. (2004), "Technical challenges of stencil printing technology for ultra fine pitch flip chip bumping", *Microelectronics Reliability*, Vol. 44 No. 5, pp. 797-803.
- Nguty, T.A., Salam, B., Durairaj, R. and Ekere, N.N. (2001), "Understanding the process window for printing lead-free

solder pastes", *IEEE Transactions Electronics Packaging Manufacturing*, Vol. 24 No. 4, pp. 249-54.

- Rodriguez, G. and Baldwin, D.F. (1999), "Analysis of solder paste release in fine pitch stencil printing processes", *Journal of Electronic Packaging*, Vol. 121 No. 3, pp. 169-78.
- Wilson, H.J. and Davis, R.H. (2002), "Shear stress of a monolayer of rough spheres", *Journal of Fluid Mechanics*, Vol. 452, pp. 425-41.

About the authors



S. R. Hillman received an MEng in Mechatronics from King's College London, UK in 2002. He was also elected as an Associate of the College (AKC). He then worked briefly as a technical assistant in broadcast engineering before returning to King's to start his PhD in 2003. His research involves the study of dense suspensions and in particular the phenomenon of jamming.

S. H. Mannan received a BA and PhD degrees in physics from Oxford University, UK, and Southampton University, UK, in 1988 and 1991, respectively. He then worked in the field of electronics packaging at Salford University, UK, and Loughborough University, UK, until 1999 when he was awarded a lectureship at King's College London, UK, and also received a 5-year EPSRC Advanced Research Fellowship investigating liquid-solid interfaces. His current interests include rheology of dense suspensions (e.g. solder paste) and packaging for high-temperature electronics. He is a member of IEEE.

R. Durairaj received a BEng with first class honours in Manufacturing Engineering from the University of Salford, UK in 1999. He is currently a research student at University of Greenwich, where his research concentrates on Microsystems Assembly Technology (E-mail: r.durairaj@gre.ac.uk).

A. Seman received a BEng in Mechanical Engineering from University of Manchester Institute of Science and Technology (UMIST), UK. He is currently a research student in School of Engineering, University of Greenwich (E-mail: a.seman@gre.ac.uk).

N. N. Ekere received an MS degree in 1984 and a PhD degree in 1987 in Manufacturing Engineering from Loughborough University of Technology, UK and the University of Manchester Institute of Science and Technology (UMIST), UK, respectively. He currently holds a chair in Electronics Manufacturing in the School Engineering, University of Greenwich, UK. He is engaged mainly in research into soldering and electronics packaging technology. Professor Ekere is a Chartered Engineer and a member of the IEE/UK (E-mail: n.n.ekere@gre.ac.uk)

M. Dusek received an MSc degree in Electronic Devices and Systems from Faculty of Electrical Engineering and Computer Science TU of Brno, the Czech Republic in 1997. As a student he contributed on the development of

optical tweezers in the Laboratory of Quantum Generators at the Institute of Scientific Instruments, Academy of Sciences of the Czech Republic. He is a Senior Research Scientist in the Electronics Interconnection Group dealing with a range of issues in electronics manufacturing, measurements and testing. Milos is leading tasks in the lead-free measurement programme, covering PCB design, reliability testing of solder joints, electronic media printing and classification of printed deposits. He is author/co-author of 30 NPL reports and 12 international conference papers.

C. Hunt graduated with an honours degree in Physics and a PhD from Surrey University in Materials Science. He heads up the electronics interconnection area at the National

Physical Laboratory (NPL). The research work at NPL enjoys significant UK government support as well as industry funded projects. The work at NPL covers a wide range within the assembly industry, and includes a significant effort on lead-free soldering, looking at aspects such as reliability, solderability, rework and inspection issues. Chris has led a European collaborative project looking at SIR testing. Other areas of interest are in printing and dispensing of solder paste, and other resin-based systems. He was part of the team that co-authored the two DTI reports on lead-free soldering. He is chair of the UK national committees in the soldering and assembly area that shadow ISO and IEC, and a member of them as well, and attends IPC committees formulating assembly standards.