

# REPORT

## Measuring Stencil Printed Solder Paste

Christopher Hunt

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by

Christopher Hunt

Centre for Materials Measurements & Technology,  
National Physical Laboratory  
Teddington, Middlesex, UK, TW11 0LW

## ABSTRACT

A methodology is described that for the first time permits the deterioration in quality of stencil printed solder paste to be followed in great detail. The techniques developed can be used in the detection of changes in print quality due to changes in printer set up. These achievements have been accomplished by developing a standard stencil, using laser profiling measurements of the printed paste, and the development of rules for analysing the profiling data. Eight parameters are defined which allow various printing characteristics to be monitored and comprehensively, providing the operator with a tool for process optimisation and paste choice.

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National Physical Laboratory  
Teddington, Middlesex, UK, TW11 0LW

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Approved on behalf of Managing Director, NPL, by Dr C Lea,  
Head, Centre for Materials Measurement and Technology

## CONTENTS

|          |                                                                           |           |
|----------|---------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>INTRODUCTION</b>                                                       | <b>1</b>  |
| <b>2</b> | <b>EQUIPMENT</b>                                                          | <b>1</b>  |
| <b>3</b> | <b>DATA ANALYSIS</b>                                                      | <b>4</b>  |
| 3.1      | Peak Height, Width and Gap                                                | 6         |
| 3.2      | Peak Balance                                                              | 7         |
| 3.3      | Peak Shape                                                                | 7         |
| 3.4      | Skipping                                                                  | 8         |
| 3.5      | Bridging                                                                  | 9         |
| <b>4</b> | <b>RESULTS AND DISCUSSION</b>                                             | <b>9</b>  |
| 4.1      | Peak Cross Sections                                                       | 10        |
| 4.2      | Peak Height                                                               | 10        |
| 4.3      | Peak Width and Gap                                                        | 11        |
| 4.4      | Peak Volume                                                               | 11        |
| 4.5      | Peak Shape and Balance                                                    | 12        |
| 4.6      | Skipping                                                                  | 13        |
| 4.7      | The Effect of Pitch                                                       | 13        |
| 4.7.1    | The Influence of Pitch on Printed Solder Paste Volume                     | 14        |
| 4.7.2    | The Influence of Pitch on the Height and Width<br>of Printed Solder Paste | 14        |
| 4.7.3    | The Influence of Pitch on Bridging of Printed<br>Solder Paste             | 15        |
| <b>5</b> | <b>CONCLUSIONS</b>                                                        | <b>15</b> |
|          | <b>ACKNOWLEDGEMENTS</b>                                                   | <b>16</b> |

|   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |     |
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| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 |

## 1 INTRODUCTION

The stencil printing process is the most problematic, and the most frequent source of defect yields, during processing. The occurrence of defects during stencil printing can be attributed to the fact that over 25 variables can be identified for this process. This problem is exacerbated, since the medium being printed, solder paste, is itself a very complex material, with time and environment dependent properties. The complexity of printing and solder paste means that users require a great deal of skill to diagnose printing failures. A tool in the armoury for diagnostics and quality control is measuring the paste height and volume. There is a very wide spectrum of available devices used to measure solder paste height, varying from simple microscopes through to sophisticated devices that can measure volumes spot heights over an entire board in less than a second. A mid range compromise device applies a line of light at 45°, and the split in the line over the paste deposit is measured to give an average height of the paste across the line. While the simple machines are excellent for detecting the presence of paste on pads, measurements of volumes are useful in determining the quality of the stencil print. All the machines measure single pads and hence no averaging is performed and no information is obtained about bridging. If a regular array of stencil prints are analysed then there are opportunities to extract a great deal more information about printing performance.

Remote sensing laser scanning height detectors are widely available and used to perform a wide range of tasks. This paper discusses the adaptation of such an instrument and a program for successfully analysing the data to yield seven basic parameters characterising solder paste printing.

## 2 EQUIPMENT

Solder paste was printed using a DEK 265Lt through a laser cut stencil as shown in Figure 1. The stencil has a number of features. The top and bottom rows of apertures are identical, but inverted. These rows contain five arrays at different pitches of, 0.6, 0.5, 0.4, 0.35 and 0.3mm, with each array containing a "X", "Y" and "XY" orientated set of 12 apertures. This nomenclature is shown in Figure 2. These arrays all have equally spaced aperture gaps and intermediate spaces. The central row has circular and slot apertures that decrease in size but maintain a constant separation. A coding nomenclature was adopted for the work for the top and bottom row of rectangular apertures. A three letter code was used, the first letter represented either the top or bottom row of aperture arrays, the second letter referred to the pitch, and the third letter the orientation. The top row of apertures in Figure 1 were called the top, and were at the beginning of the print stroke for the boards taken for analysis. The letter for the pitch ranged from A to E as indicated in Figure 1. The letter for orientation could be either X, Y, or XY. For example, "tcx", is the aperture name for the X orientated 0.4 mm pitch aperture array on the top row.

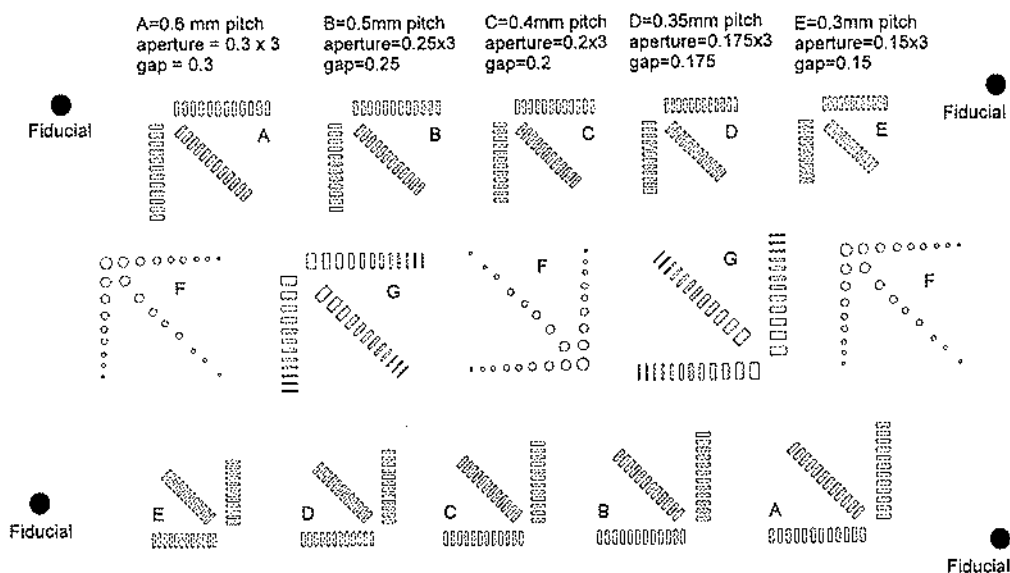


Figure 1: Stencil layout used for printing studies

This stencil permits the efficiency of printing in different orientations between the squeegee and apertures to be evaluated, as well as measuring the print quality at the beginning and end of the print stroke. Printing was performed onto 3mm thick copper plates. Using copper plates guaranteed a flat substrate and avoided gasketing issues.

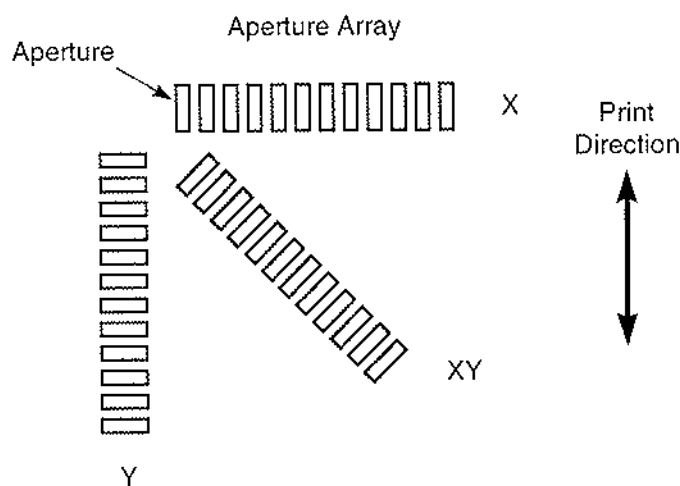


Figure 2: Definition of aperture orientations

The stencil prints were measured using a Rodenstock Laser Stylus RM600 profilometer, which was located remotely from the DEK printer. The arrangement is shown in Figure 3. The Rodenstock has a  $1\mu\text{m}$  focused spot and was operated on a  $\pm 300\mu\text{m}$  range with  $0.2\mu\text{m}$  sensitivity. The machine is capable of measuring on a  $\pm 3\mu\text{m}$  range with  $0.01\mu\text{m}$  sensitivity. The Rodenstock carries out an internal calibration for the z axis (to within  $\pm 3\mu\text{m}$ ). In the exploratory work reported here only the A, B and C apertures were used. With D and E apertures bridging was too prevalent, and they could not be used successfully. For each Rodenstock scan the copper plate was orientated so that the individual aperture arrays were always in the same orientation on the Rodenstock. Hence, all scans were carried out in the same direction regardless of the print direction or the aperture orientation, be it X, Y or XY.

Therefore, the start point was defined in all cases as the bottom left hand corner of the aperture array, and was referenced as 0.00, 0.00, as shown in Figure 4. Scanning was always performed left to right and upwards. Since the aperture arrays had different widths, due to the various pitches, the scan widths were adjusted accordingly. The aperture array with the respective scan sizes are given in Table 1.

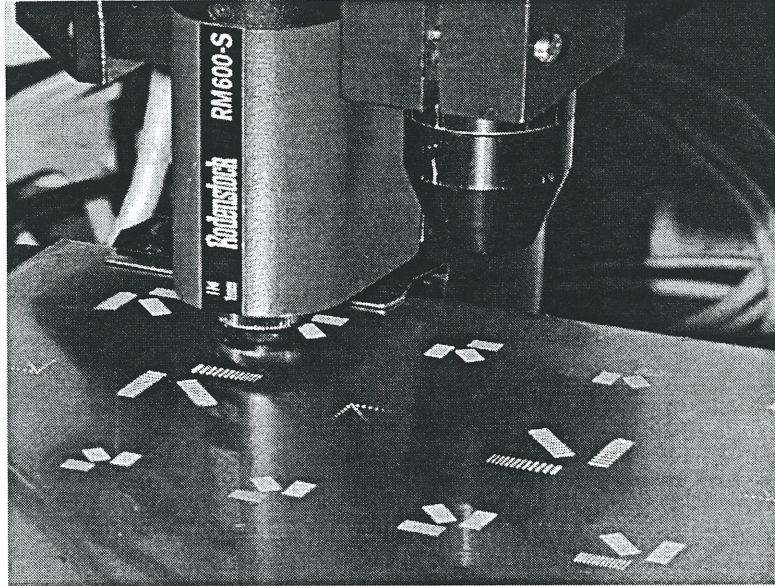


Figure 3: Measurement arrangement of stencil prints with Rodenstock

Table 1: Aperture Array and Scan Sizes (mm)

| Pitch | Aperture Name | Array Width | Array Length | Scan Width | Scan Length |
|-------|---------------|-------------|--------------|------------|-------------|
| 0.6   | A             | 3.0         | 6.90         | 3.6        | 8.0         |
| 0.5   | B             | 3.0         | 5.75         | 3.6        | 6.8         |
| 0.4   | C             | 3.0         | 4.60         | 3.6        | 5.8         |

The Rodenstock was set to scan at 3.3 mm/s, with 55 scan lines in the "Y" direction, and 1500 data points in the "X" direction. The scanning details for an individual aperture array are shown in Figure 4. Hence for each aperture array there are 82,500 data points, and a scan time of approximately 3 minutes.

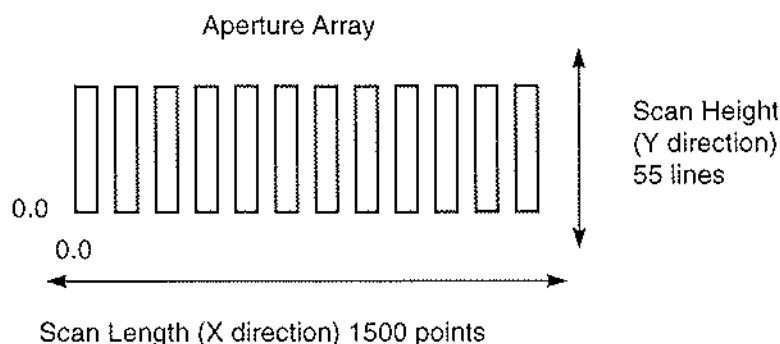


Figure 4: A single aperture array with the axes and the number of data points defined

### 3 DATA ANALYSIS

To take advantage of the large amount of data for each aperture array, and the fact that there were 12 identical aperture prints within each array, a procedure was required that could analyse the whole array and produce parameters that were an average of the 12 prints.

For any program to achieve an averaging of the whole aperture array two requirements must be met. First, the scanned data from the Rodenstock, the matrix of numbers, must have a horizontal baseline in both axes, and second, the axes of the 12 prints must be orthogonal with the axes of the matrix. In the raw data from the Rodenstock these two conditions are never precisely met, since the substrate on which the paste is mounted, never sits perfectly flat relative to the Rodenstock horizontal plane. Moreover, the axis of the aperture prints does not perfectly align with the scan axes of the Rodenstock.

The levelling was achieved simply by calculating the slope between the corners in both X and Y axes of the matrix and then subtracting an interpolated baseline from the matrix. This operation successfully levelled the matrix. The second requirement of the prints being orthogonal was achieved by first finding the centre line of each print along the Y direction, (axes for individual aperture prints are the same as for the aperture array, as defined in Figure 4). Next along each centre line, and five data rows either side, the data were scanned up each column in the Y direction to find the point at which the height increased above  $30\mu\text{m}$ . The median of these 11 numbers, along with the centre line, were taken as defining the tip or leading edge of each of the 12 prints. A linear regression fit was made to these points, and correcting for the number of data points per millimetre, the arctan was taken to give the twist on the measured results. An interpolation routine was then run to twist the matrix to the correct orientation, setting the corners to zero where there were no data. A similar routine could be run if the matrix still appeared to be sheared, which can be visualised as the long axis of the prints not being parallel to the scan axes. By taking the average slope of the centre lines for the 12 aperture prints and calculating the arctan as before, a similar correction could be made to the matrix. With the matrix now flat and correctly orientated the measurement of the prints themselves could begin.

An example of just one print extracted from a measurement of a complete set of 12 prints is shown in Figure 5, after correcting for flatness and orientation. The print in Figure 5 was from a "b" aperture (0.5mm pitch), X orientation and the top row as shown in Figure 1.

Note that Figure 5 is a distorted representation, since the scales on the axes are not of equal magnitude due to the scan widths and the number of sampled data points. It is clear from Figure 5 that this fairly typical solder paste print does not have a very flat top and that the base is considerably wider than top. The irregular nature of the paste print on the fine scale can be seen in a scanning electron microscope (SEM) image, shown in Figure 6. Note this is not the same aperture print as shown in Figure 5.

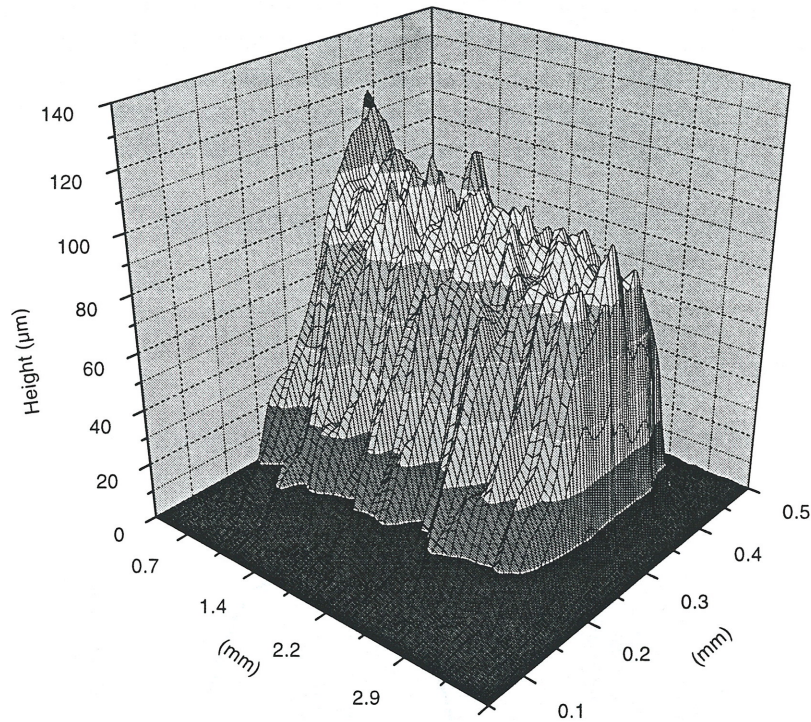


Figure 5: A surface mesh of one aperture slot (tbx)

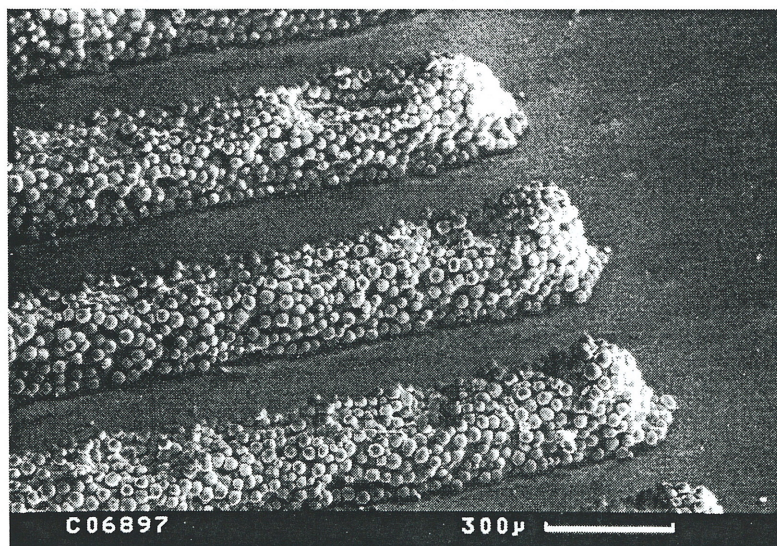


Figure 6 SEM image of solder paste print

Both Figure 5 and 6 illustrate the potential deficiencies in single point measurements in terms of only sampling a limited amount of data. In Figure 5 for example the height of the

top of the print varies between 90 and 130 $\mu\text{m}$ . A procedure that analyses all the data in a single aperture print to produce parameters that are an average will obviously be superior to single point measurements, and if all 12 aperture prints are measured the statistics will be enhanced still further. Moreover, information can be extracted from the aperture array on the degree of bridging in the space between prints.

The approach adopted here was to measure each aperture print in turn and take an average curve for each and then average all 12 prints at the end. Two cross sections were produced, i.e. across the aperture print in the X direction, and along the aperture print in the Y direction. In the X direction this was approximately 40 cuts across each print, with approximately 100 points in each curve. The second of these was 11 cuts along each print with 55 points in each. Clearly, the data quality was higher in the first section.

The various parameters defined in the work are now discussed.

### 3.1 Peak Height, Width and Gap

An idealised curve is shown in Figure 7 defining peak height, peak width and peak gap.

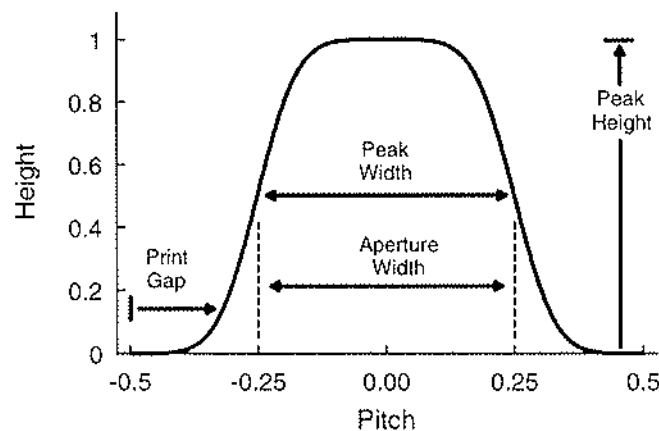


Figure 7: Schematic of aperture print cross section, defining various parameters

In Figure 7 the axes have been normalised. The height is expressed in terms of the stencil thickness, and the width of the print in terms of the pitch. Hence, an idealised print would have a height of one and width of a  $\frac{1}{2}$ . Three parameters are defined in Figure 7, the peak height, peak width and print gap. The peak height is the height at the mid-point of the average aperture section, and the width is taken at half the peak height. The print gap is actually measured by taking the width of the print profile at 15 $\mu\text{m}$  and subtracting that from the pitch, to produce the gap between neighbouring prints. The aperture width is also marked on the schematic, and is useful for illustrating that the printed area outside the aperture can be calculated and hence the amount printed off the pad estimated.

### 3.2 Peak Balance

A number of other parameters are defined. The first one we consider is the balance between the left and right of the print. In Figure 8 a schematic is shown for a width cross section. This calculation can also be done for the length cross section. The measured part of the curve is taken as that within the aperture space. It is easy to envisage that this balance parameter would be useful in investigating the effect of printing direction and squeegee type.

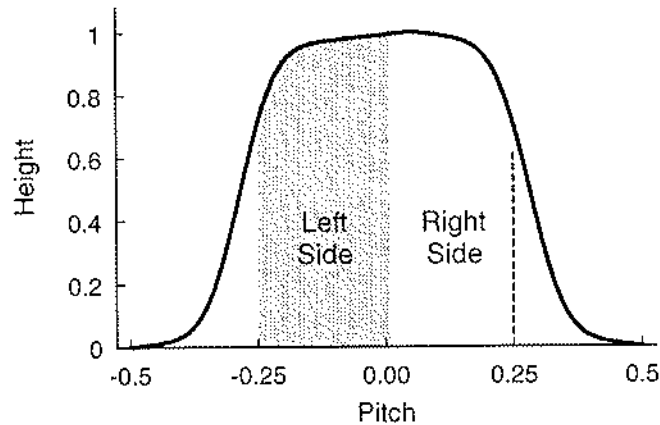


Figure 8: Schematic of aperture print cross section, defining the balance parameter

### 3.3 Peak Shape

The peak shape factor is defined by constructing a horizontal line where the mid-peak position crosses the print profile. Then within the defined aperture space the area is measured between the horizontal line and the print profile. If the print profile is below the horizontal line the area is defined as being negative, and above as being positive. This construction is illustrated in Figure 9, and the three shaded areas are summed.

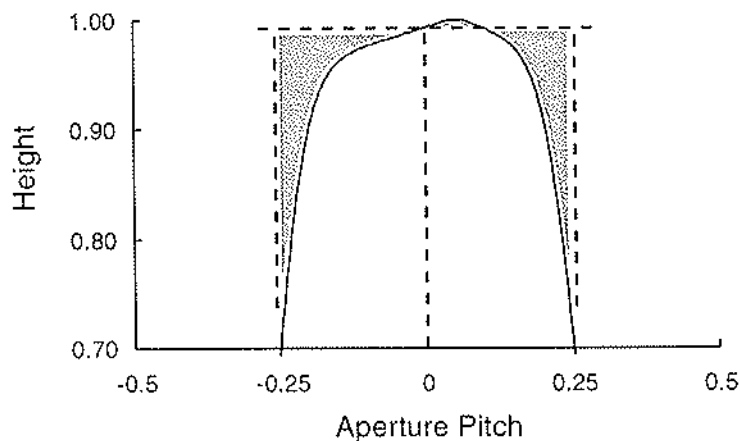


Figure 9: Schematic of aperture print cross section, defining the shape factor.

Possible examples of print profiles are shown schematically in Figure 10. It is immediately clear from these drawings how such a shape parameter may be useful in characterising

printing. In particular if the shape factor is positive, as in (c), that this is indicative of the print edges being pulled up as the board drops away from the stencil. In drawing (a) the shape factor is negative, which is typical of sections in the width or X direction of the print. Drawing (b) is more unusual, but is sometimes seen in the length or Y direction of the print. Drawing (d) has an identical shape factor value as (b) but is clearly different; this dilemma is simply resolved by looking at the balance parameter, which will be different between the two examples. Shape (d) will be most often observed in the length cross section of an aperture which is aligned with its Y axis along the print direction. Under this condition the paste is frequently preferentially deposited at the end of the squeegee stroke over the aperture. Shape (c) may be indicative of when the board separation speed is too high and the paste is being pulled up around the edges.

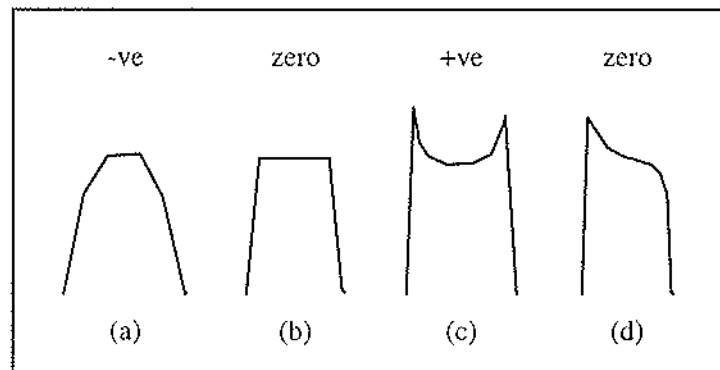


Figure 10: Schematic of possible print profiles and the shape factor values.

### 3.4 Skipping

In any individual aperture print a defect may occur that is schematically shown in Figure 11. In this defect part of the paste print is missing, this may be a whole segment as shown in Figure 11, or it may be smaller bites which do not completely bisect the print.

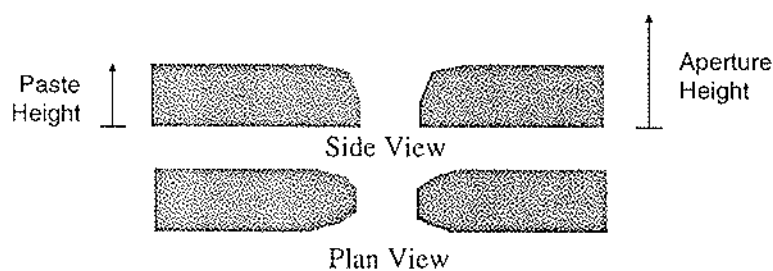


Figure 11: Schematic of skipping during printing

The degree of skipping is calculated for each aperture print singularly; it is not done on an average of all the prints in the aperture array. First, the mean of the heights along the centre line of each print is taken, but only where the height is greater than  $30\mu\text{m}$ . The real volume of the each print is then measured, but only within the defined aperture space. This value is compared with a calculated value for that print using the mean height and assuming a cuboid deposit, and the ratio of the measured and calculated values taken. We would not expect the ratio for any print to have a value of 100% since most aperture prints have a

Gaussian type profile in the X cross section. Results for good quality prints and no skipping produce skipping values between 70 and 90%. Values less than this are indicative that skipping is occurring to some degree.

### 3.5 Bridging

Bridging is easy to visualise, simply consisting of solder paste between the aperture prints, as shown schematically in Figure 12. The bridging considered here is termed as "wet bridges", since after reflow some bridges may collapse under the surface tension effects of the molten solder. To calculate the level of bridging the eleven spaces that are between the prints are examined. The conditions that have to be met for detecting a bridge are as follows. The bridge must be continuously greater than  $10\mu\text{m}$  across the gap for the start of a bridge to be registered. When this occurs the bridge counter is incremented by one, and a bridge found condition is switched on. The  $10\mu\text{m}$  condition is tested on successive slices of the data within the gap, and the position at which it fails is noted, and the bridge found condition is switched off. The height of the bridge and the volume of the bridge are calculated. All eleven gaps are analysed for bridges. Hence the number of bridges, the total volume for all the bridges, the mean bridge volume, and the height of the bridges are recorded.

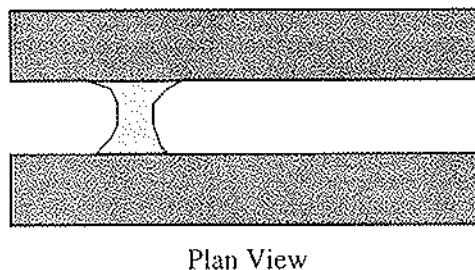


Figure 12: Schematic of bridge

## 4 RESULTS AND DISCUSSION

The use of the tools developed above are now illustrated by discussing the output from such an analysis on a stencil printed solder paste on a specific aperture. A ubiquitous RMA solder paste, using the "tcx" aperture in a  $150\mu\text{m}$  laser cut stainless steel stencil was used. The temperature and humidity during printing were controlled at  $22^\circ\text{C}$  and 40%RH. In this example the paste was evaluated over a 6 hour period, using polyurethane (hard) squeegees. Approximately 200gm of paste was loaded onto the stencil and the roll was not replenished during the day. At the start of printing, 10 strokes were performed on a blank part of stencil, and then the paste roll was moved to print through the apertures. The following procedure was then carried out and repeated every 2 hours. Six prints were made on to the copper plates and the last one was taken for analysis on the Rodenstock Profilometer. The paste roll was then moved back to the blank part of the stencil. The apertures were cleaned and air blown twice. The paste was then printed continuously for 2 hours on the blank part of the stencil, equivalent to 300 pseudo prints. The paste was then moved to print through the apertures, and the procedure repeated. Hence prints were taken for analysis at 9am, 11am, 1pm and 3pm.

#### 4.1 Peak Cross Sections

In Figure 13 and 14 are shown the width and length cross sections respectively. Each curve as described before is the average for the aperture array, all the sections for each aperture print. The solid line is the first print at 9am, and for this particular solder paste, with successive prints during the day the print height diminishes. Also for the width section the width decreases with time.

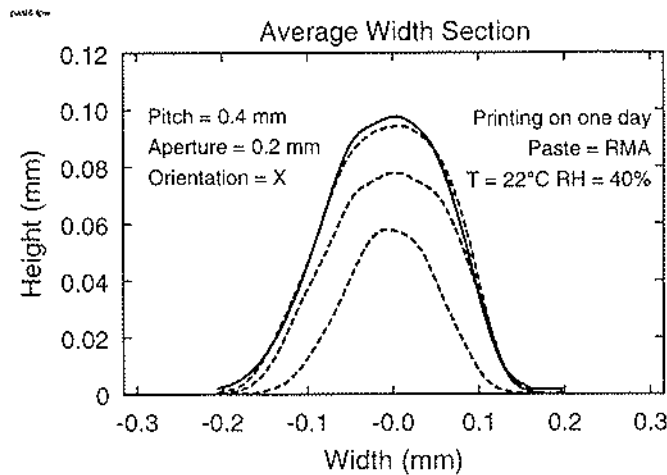


Figure 13: Average width peak section (X direction)

It is clear for both the width and length prints this particular paste does not show any propensity for the balance or shape to shift away from the normal print pattern. Both figures also show that the mean print height starts off around 100 $\mu$ m, two thirds of the stencil thickness.

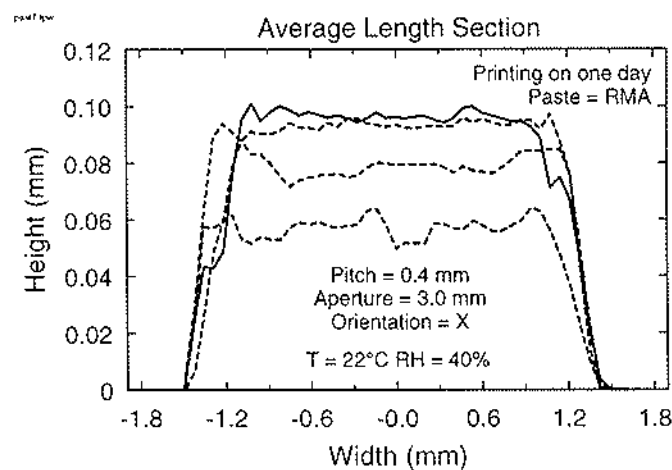


Figure 14: Average length peak section (Y direction)

#### 4.2 Peak Height

In Figure 15 the maximum and mean peak heights are plotted as a function of the time of day. The maximum peak height is simply the maximum height from any point in the aperture array. The mean height is the mid point of the average width cross section. It is clear that the mean peak height is more time dependent than the maximum peak height.

This is indicative of how much more reliable the mean height will be in following printing behaviour than a single point measurement. The fall in mean height is similar to that observed in Figures 13 and 14.

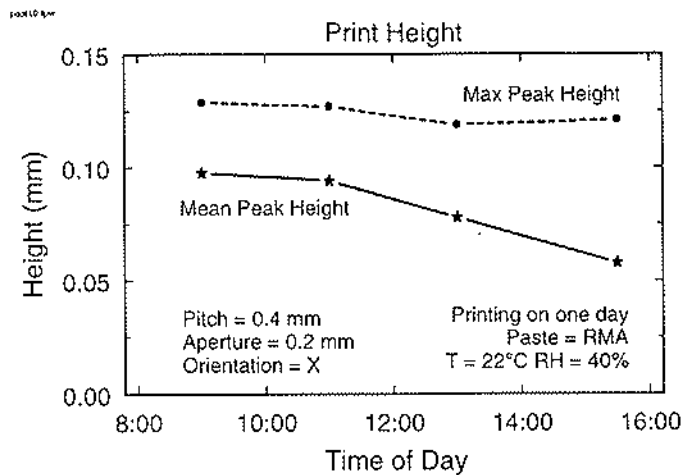


Figure 15: The average and maximum peak heights as a function time during printing

#### 4.3 Peak Width and Gap

Figure 16 shows how the peak width and gap changed with time during printing. The width and gap are both expressed in terms of the aperture pitch, and ideally they will have values around 50% for a square cross section. It is clear that the peak width is constant for the first four hours of printing and then becomes thinner. The gap shows the inverse behaviour.

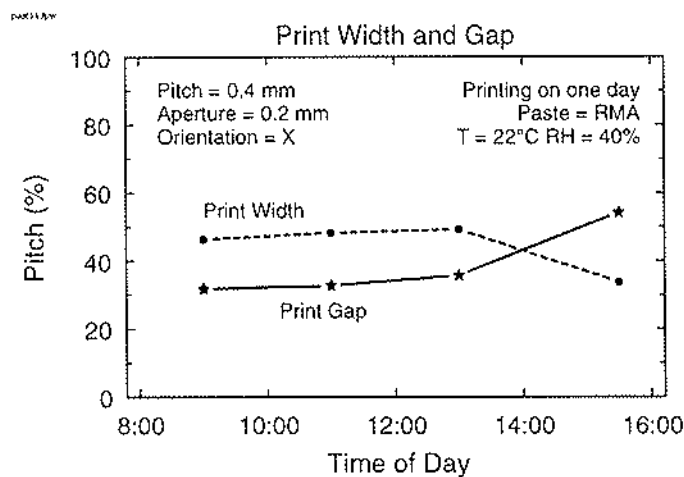


Figure 16: Peak width and peak gap as a function time during printing

#### 4.4 Peak Volume

In Figure 17 the peak volume and the width insufficiency are plotted, and both are plotted as a ratio of the total possible volume. The total volume is simply calculated by summing all

the data points in the aperture array irrespective of their location. The width insufficiency is calculated as one minus the volume ratio, but in this case calculating the volume only within the aperture space. This calculation not only shows the flexibility of the program, but is useful in showing how much paste will be printed on the pad, assuming a 1:1 stencil and pad area. This calculation uses the average width section. This small difference explains why the gradients of the curves are different. The width insufficiency curve follows very closely the behaviour of the inverted mean height curve, whereas the total volume curve shows the volume holding up better after 4 hours printing and then falling away after 6 hours. Calculating volumes within the aperture space may be useful if significant paste is being printed off the substrate pads.

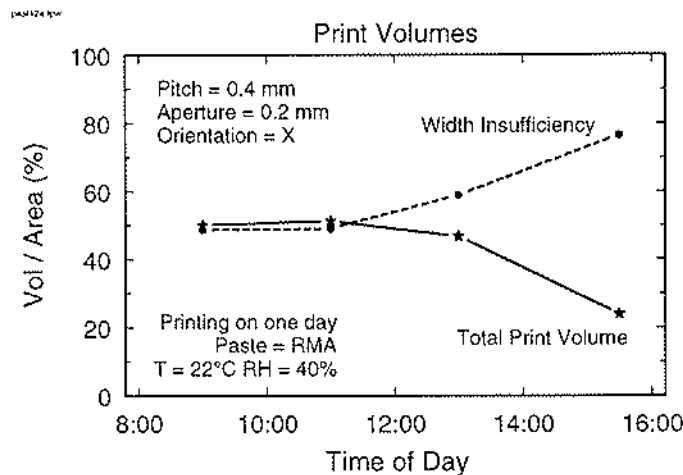


Figure 17: Peak volume as a function time during printing

#### 4.5 Peak Shape and Balance

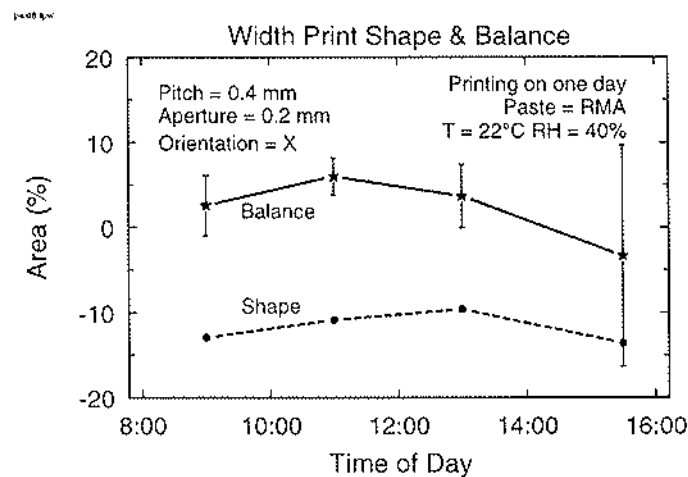


Figure 18: Peak shape and balance as a function time during printing

Examples of peak shape and balance are given in Figure 18 for the width section. The shape values are quite negative, reflecting the Gaussian shape of the aperture print profile, and do not show any significant change in value. The balance values are close to zero reflecting the

symmetry observed in Figure 13, but also highlighting the subtle changes that can be followed with this parameter which a visual inspection of Figure 13 does not readily reveal. Error bars on the balance curve are presented to illustrate the repeatability across an aperture array and are derived by splitting the 12 aperture slots into three sets of four, of left, middle and right, and taking the average and standard deviation of the three sets. This shows the level of repeatability across an aperture array. Normally the parameters from the processed data from an aperture array are only plotted as a single point. The last set of data taken at 16:30 show how the print uniformity is deteriorating along with the overall print quality seen above.

#### 4.6 Skipping

The degree of skipping is plotted in Figure 19 as a function of printing throughout the day. The solid curve is the average for all 12 aperture slots, and the maximum label refers to where the most skipping has occurred in a single aperture slot, and the minimum label refers to where the least amount of skipping has occurred. The initial level of skipping is just over 70% and reflects the profile seen in Figure 13. For the first 4 hours of printing the degree of skipping is approximately constant, and then falls off sharply in the last two hours; revealing that the paste is no longer printing consistently and the likelihood of detecting skips and mouse bites in the individual aperture prints is increasing. This observation was confirmed visually. The maximum level of skipping, at less than 40%, indicates that only half the paste is being printed on particular pads and could easily result in opens during assembly.

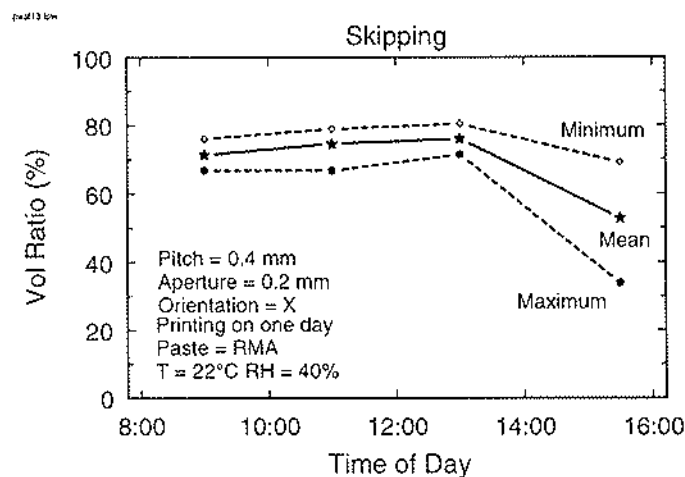


Figure 19: Skipping as a function time during printing

#### 4.7 The Effect of Pitch

In the above we have followed the behaviour of a specific aperture array during one days printing with a constant roll of solder paste. There are other ways of examining and presenting the data from such an experiment. Perhaps the most useful and illuminating analysis is to investigate how a paste performs as a function of aperture pitch. The next three Figures look at the influence of aperture pitches, 0.4, 0.5 and 0.6 mm, on the performance of a different solder paste, a no-clean paste. The same experimental run was

used under the same conditions. The three parameters considered are the volume of paste printed, the height and width, and finally the bridging.

#### 4.7.1 The Influence of Pitch on Printed Solder Paste Volume

The volume of solder paste printed is shown in Figure 20 for the three different aperture pitches, 0.4, 0.5 and 0.6 mm. The volume axis has been normalised for each aperture. Even so we can see that, comparatively, less paste is being printed at the finer pitches. There is also slightly more decrease in volume with the time of day as the pitch becomes finer. The final data point for 0.4 mm pitch is not plotted since the level of bridging had increased to a point where analysis of the laser profiling data was no longer feasible. We shall see when looking at the next two set of results that the volume of paste is comparatively stable, and that it is other factors of the paste quality that are far more sensitive to ageing of the paste.

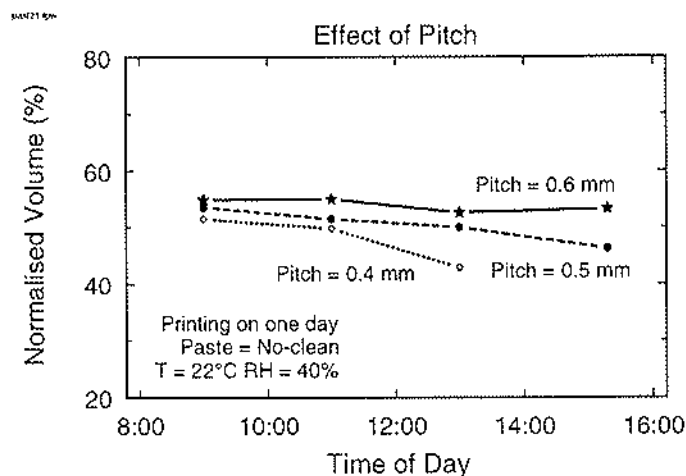


Figure 20: The influence of aperture pitch on the volume of printed solder paste as a function time during printing

#### 4.7.2 The Influence of Pitch on the Height and Width of Printed Solder Paste.

In Figure 21 the ratio of print height to width is plotted as a function of the time of printing. The height and width values taken for the ratio are themselves normalised units. Hence, the height value is ratioed to the stencil thickness, and the width is ratioed to the pitch. Therefore if a print is as high as the stencil and has a width equal to the pitch, then the ratio would be two. If the height collapses and the width increases with printing, then this ratio will drop quickly, providing a sensitivity much more than obtained by inspecting either value singly. Figure 21 shows that print quality deteriorated equally for all three aperture pitches during the first two hours, although we can see from Figure 20 the volume did not really change. The gradients on these plots are significantly steeper than seen in Figure 20, showing how more sensitive this ratio is compared to straight forward measurement of volume. After 4 hours of printing the 0.4 mm pitch results show a dramatic fall in the ratio, whereas the 0.5 and 0.6 mm values show a steady fall. After 6½ hours printing the 0.4 mm print is no longer measurable and the 0.5 mm data has fallen to a very low value, and the 0.6 mm results show only a small fall. The ratio of height over width is clearly a sensitive parameter at tracking the deterioration in print quality and small deteriorations in print

quality (not observed in other parameters) can be detected. However, perhaps the next results present the really significant test for paste performance.

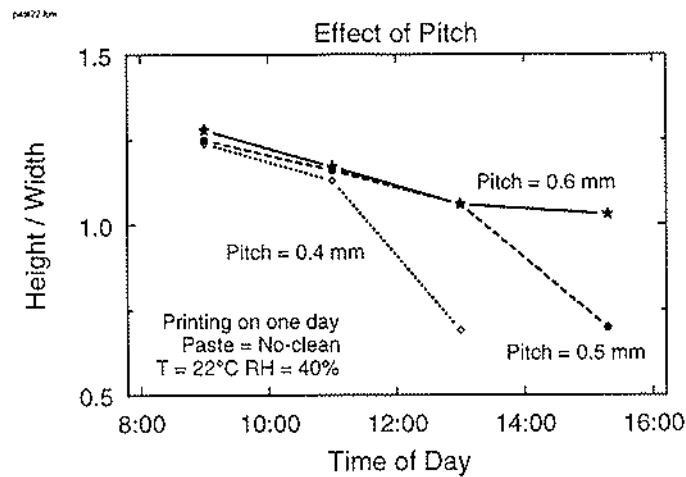


Figure 21: The influence of aperture pitch on the height and width of printed solder paste as a function time during printing

#### 4.7.3 The Influence of Pitch on Bridging of Printed Solder Paste.

The degree of bridging is plotted as a function of aperture pitch in Figure 22. The number of bridges is clearly a function of pitch and shows how at fine pitches the level of bridging becomes a far more severe problem. For example, it is not possible to analyse the profiling data at 0.4 mm pitch after printing for more than 4 hours due to the high level of bridging. The level of bridging may well be the most useful assessment of a pastes printing quality, but currently it is not a characteristic that is often measured. The data here show how at 0.6 mm pitch it is possible to keep printing over extended periods. It should be emphasised that the bridging described here are wet bridges, and many will collapse during reflow, and that the results are for a constant roll of paste without any replenishment during the experiment.

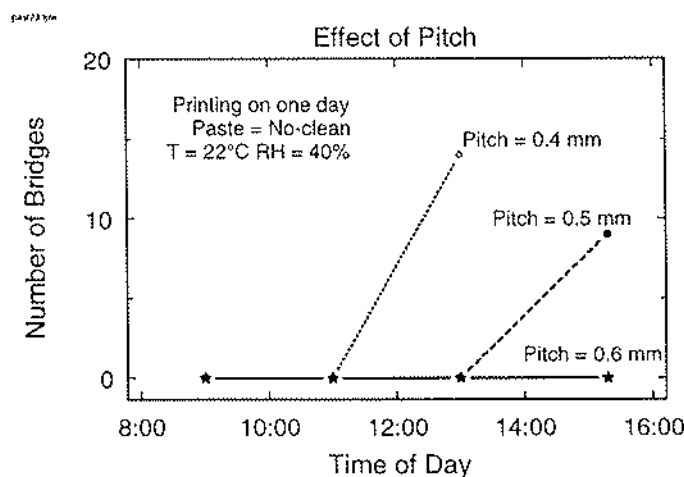


Figure 22: The influence of aperture pitch on bridging of printed solder paste as a function time during printing

## 5 CONCLUSIONS

This paper discusses a novel method for the comprehensive characterising of stencil printed solder paste. It is based on three key elements: a standard stencil pattern, laser profiling of the printed paste, and a program to analyse and characterise the profiling data.

Eight basic parameters are developed: volume, mean height, mean width, mean gap, peak balance, peak shape, skipping and bridging. It is possible to combine these parameters.

Examples are presented where these parameters are used to track printing performance to illustrate their value.

In future work these techniques will be used to analyse various aspects of stencil printing.

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