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Investigation of Printing Performance of Solder Paste at Different Temperatures

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Abstract
The properties of solder paste are immensely affected by temperature variations and humidity. Apparently, temperature plays a vital role in achieving reliability in print performance and good quality. The printing performance of the solder paste at different temperatures was investigated using two types of lead-free solder paste. Three temperatures were investigated under three different time intervals. Issues to be considered are the solder paste deposit defects associated with the pre-printing temperatures.
Keywords: Surface Mount Technology, Printed Circuit Board Assembly, Slump test, Reflow Soldering, Solder Paste.

I. Introduction

As the trend toward miniaturization and compact product continues, the assembling process of the electronic component or surface mount devices (SMDs) becomes more complex and there is a need for some form of automation (Lau *et al.* 1996). The automated process of assembling the electronic component or surface mount devices is known as *Surface Mount Technology (SMT)* by means of using solder paste as interconnecting material to provide electrical, thermal and mechanical function (Huang et al, 2002, and Nguty et al, 2001).

Majority of the components used on a printed circuit board assembly (PCBA) are based on surface mount technology (SMT) being assembled using solder paste printing (SPP) and then fixed by the reflow soldering (RS) process (Lau and Yeung 1996). There are three major challenges in the fine pitch stencil printing process. These challenges are the solder paste formulation, the stencil manufacturing process and the optimisation of the process parameters in stencil printing Stencil printing account for a great percentage of defects in surface mount technology. A major course of these defects is the solder paste behaviour during stencil printing, which is greatly affected by temperature. As a result, it is necessary to carry out an intensive study on the effects of temperature on solder paste with respect to its printing performance (Durairaj et al, 2002).

II. Experimental design

2.1 Test materials

Two commercially available lead-free solder pastes P1 (LF318) and P2 (LF328) prepared from fluxes F1 and F2 were used. The solder particles for all the paste samples are made of the same tin-silver-copper alloy with a melting point of 217˚C. Both P1 and P2 have a percentage metal loading of 88.5%. P1 is a Type 3 solder paste and P2 is Type 4. The flux medium makes up for 11.5% of the solder paste weight. The flux medium contains a stable resin system and slow evaporating solvents with minimal odour. The formulation meets the requirements of the Telcordia (formerly known as Bellcore) GR-78-CORE and ANSI/J-STD-004 for a type ROL0 classification.
The two lead-free solder pastes LF318 and LF328 used in this experiment were separated into nine different jars respectively, making it eighteen jars in a whole. Each jar contained one hundred grams of lead-free solder paste. This separation was to allow for the number of experiments that was carried out in the study. For quick and easy identification, LF318 was named P1 and LF328 was named P2. The temperatures under investigation were 15˚C, 25˚C, and 35˚C. As shown in table 1 below, two solder pastes P1 and P2 were stored at each of these temperatures for 24hours, 48hours, and 72hours respectively, making it nine experiments for each solder paste.

Table 1: Storage parameters for P1 and P2 at the thermal chamber.

Solder paste	Temperature (˚C)	Storage time (minutes)	Storage time (minutes)	Storage time (minutes)
P1	15(˚C)	1440	2880	4320
P2	15(˚C)	1440	2880	4320
P1	25(˚C)	1440	2880	4320
P2	25(˚C)	1440	2880	4320
P1	35(˚C)	1440	2880	4320
P2	35(˚C)	1440	2880	4320

III. Process parameters

The printing parameters used for the experiment are outlined in table 2. Previous work reported by Marks et al (2007) was used as a benchmark.

Table 2: Printing parameters

Printing parameters	Values used
Printing/Squeegee speed	20mm/sec
Squeegee loading (or pressure)	8kg
Separation speed	100% (3mm/sec)
Snap-off/Print gap	0.0mm (On-contact printing)

IV. Experimental result

All the results recorded were put into the Gauge calculator. The R&R% got was 19.43%. This is well below 30% which is the acceptable standard. This means that the measurement device is capable of the task.

Plotting the average

In the formation of solder joints, print thickness determines the volume of solder in the joint. The thickness of the paste print is determined by the thickness of the metal mask of the stencil. Though stencil thickness controls the paste thickness, other variables such as snap-off height and the condition of the printing equipment determine the print height. The reflow solder height is not just a factor of solder paste height only, but also the metal content of the paste. Due to the fact that the print gap for the experiment is 0.0mm, the snap-off height becomes the thickness of the stencil which is 125µm. Therefore at this stage, the average of the average heights got from the regions in the chosen locations on the stencil was computed.

In each of the two locations under investigation, four regions were measured. In each region, two deposits were measured. The averages of the two deposits were taken. Subsequently, the averages of the locations were then computed based on the four regions. A sample of the 3-D image of the measured heights is shown in figures 1 and 2. Figure 1 shows the height of P1 while figure 2 shows that of P2. The blue base indicates the reference point, which is surface of the substrate. The red colour indicates maximum height. The results from the computed averages are shown in Tables 3 and 4, while figures 3 and 4 shows the graphs of the computed average height against the solder paste storage/aging time with respect to the storage temperatures.

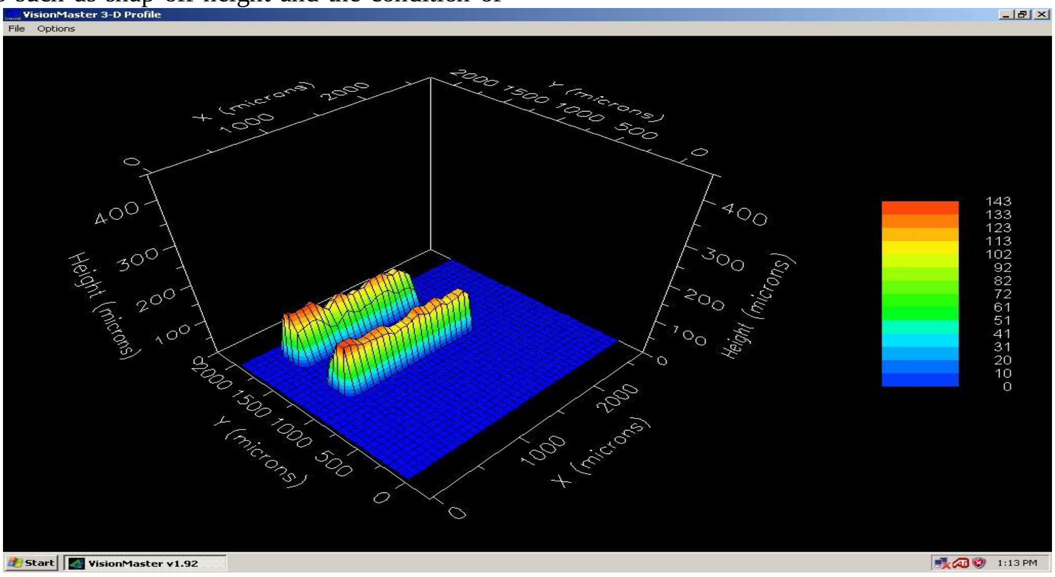

Figure 1: 3-D image of the solder paste deposit for location 1

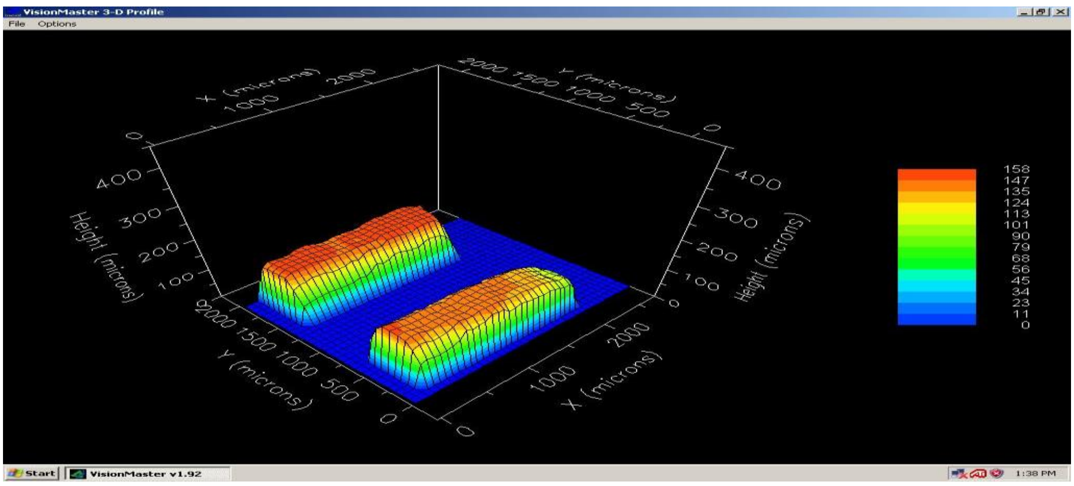

Figure 2: 3-D image of the solder paste deposit for location 2

Table 3: Results for solder paste deposit heights for LF318.

LF318 = P1					
Storage temperature (˚C)	Storage time (Hours)	Target height (µm)	Height for Location 1 (µm)	Height for Location 2 (µm)	Average height (µm)
15	24	125	103.36	89.5	96.43
15	48	125	91.63	109.66	100.65
15	72	125	92.24	115.9	104.07
25	24	125	89.15	115.58	102.37
25	48	125	83.48	122.74	103.11
25	72	125	102.08	116.79	109.44
35	24	125	100.25	120.15	110.2
35	48	125	95.26	118.69	106.98
35	72	125	112.02	119.43	115.74

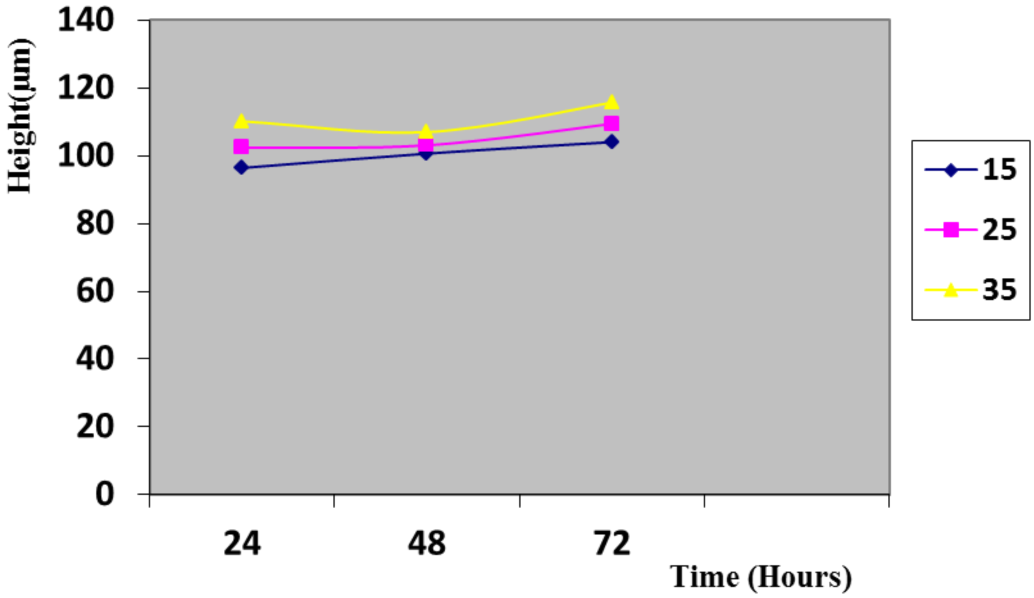

Figure 3: Temperature effect results for solder paste deposit height for LF318

Table 4: Results for solder paste deposit heights for LF328

LF328 = P2					
Storage temperature (˚C)	Storage time (Hours)	Target height (µm)	Height for Location 1 (µm)	Height for Location 2 (µm)	Average height (µm)
15	24	125	120.83	103.06	111.95
15	48	125	89.63	109.66	99.93
15	72	125	92.24	108.31	96.76
25	24	125	108.5	126.26	117.38
25	48	125	98.49	102.08	100.29
25	72	125	100.21	11538	107.80
35	24	125	99.63	114.48	107.06
35	48	125	110.15	133.9	122.03
35	72	125	117.14	129.48	123.31

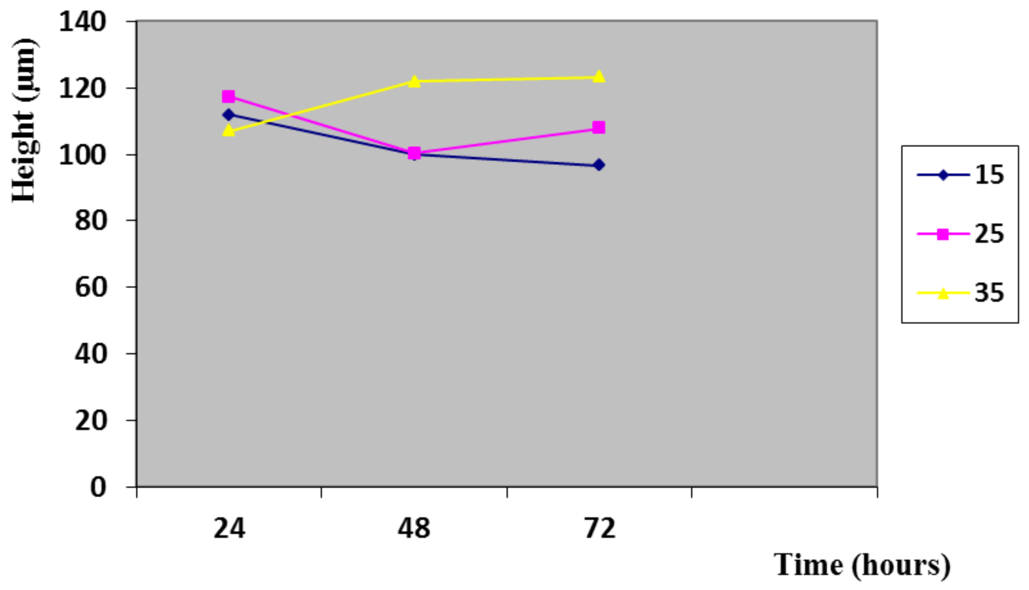

Figure 4: Temperature effect results for solder paste deposit heights for LF328

During the printing process for LF318 aged at 15˚C for 24 hours, the solder paste just rolled minimally. The temperature of the solder paste during the printing was low, and that had a great effect on the solder paste viscosity. The low temperature made the solder paste viscosity to be too high. The temperature was not conducive for the rheological properties of the solder paste to be at its best. Therefore, the paste could not role, giving rise to skipping and low aperture filling which in effect caused ragged edges. This was one of the contributing factors to the low height seen after the printing. This is evident from the points of the height for 15˚C in figure 1.

It can be observed that as the temperature increased, the height against time also increased. This trend was seen for both P 1 and P 2, except for P 2 stored at 35˚C for 24 hours. Normally, it would be expected that increase in temperature would give rise to decrease in height, given that higher temperature would cause the solder paste to slump. Rather than decrease the height as the temperature increased, the height was increasing. This is because at low temperature, the paste's viscosity increases causing the solder paste flow to slow down or not to flow at all.

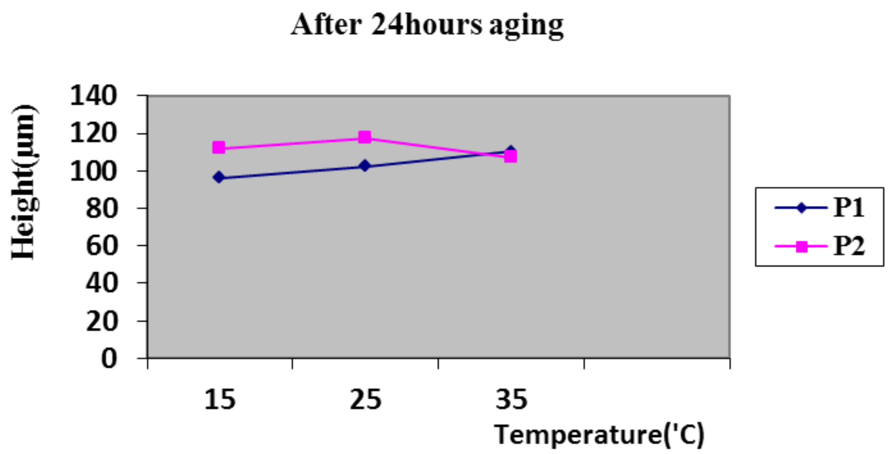

Figure 5 (a): Comparing solder paste deposit heights of P 1 and P 2 for 24 hours aging.

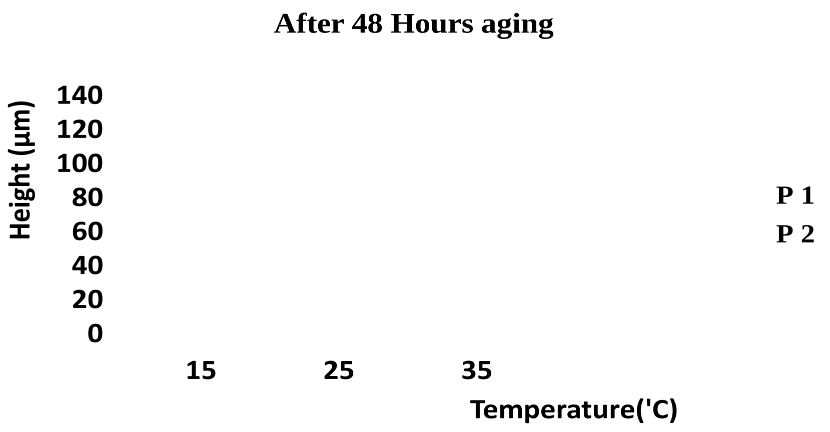

Figure 5 (b): Comparing solder paste deposit heights of P 1 and P 2 for 48 hours aging

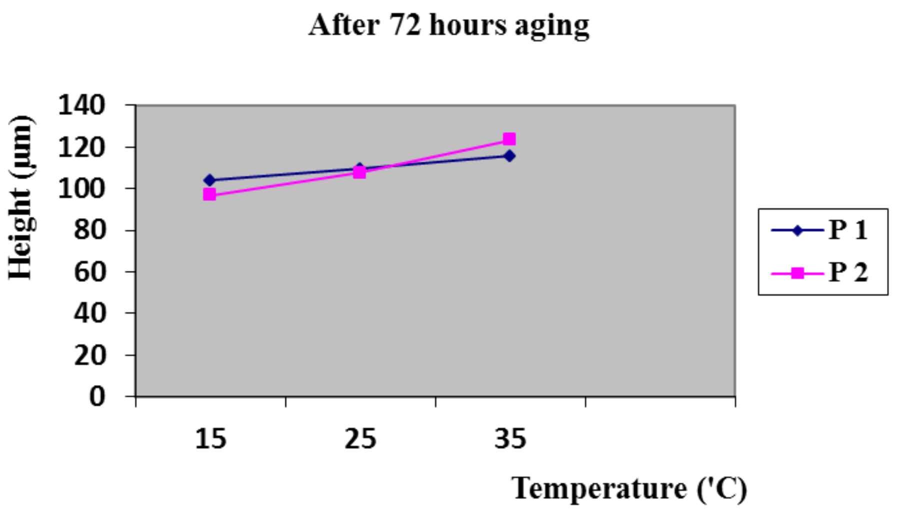

Figure 5 (c): Comparing solder paste deposit heights of P 1 and P 2 for 72 hours aging

When the solder pastes were compared, it was found as shown in figures 5 (a), (b), and (c) that the height increases as the temperature increases. This trend was seen as earlier discussed, for all the experiments except for P2 aged/conditioned at 35˚C for 24 hours. This shows that increase in height with increase in temperature and or storage time is common for both P1 and P2. Judging from common trend of increased height with increased temperature, the behaviour of P2 conditioned at 35˚C for 24 hours may be a special cause of variation.

Considering the relationship between paste heights, ability of the solder paste to roll during printing, viscosity, temperature and time, the results got in this experiment was compared with that got by Nguty and Ekere (2000). It was shown that there was an increase of 60% in paste viscosity for samples kept at room temperature apparently, longer time and higher temperature increases viscosity thereby increasing the tendency of the solder paste to roll. However, the temperature must not be excessive.

V. Variability analysis

5.1 Standard Deviation : The following mathematical equation is used to calculate the standard deviation.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}, \quad [1]$$

$$\sigma = \sqrt{\frac{(x_1-\mu)^2 + (x_2-\mu)^2 + \cdots + (x_N-\mu)^2}{N}}, \quad [2]$$

Where σ is the standard deviation, μ is the mean

This means that the standard deviation σ is the square root of the average value of $(X-\mu)^2$. Therefore, to calculate the standard deviation of the solder paste heights, we compute the difference of each data point from the mean, and then square the result.

A normal standard deviation plot should look like figure 6 below.

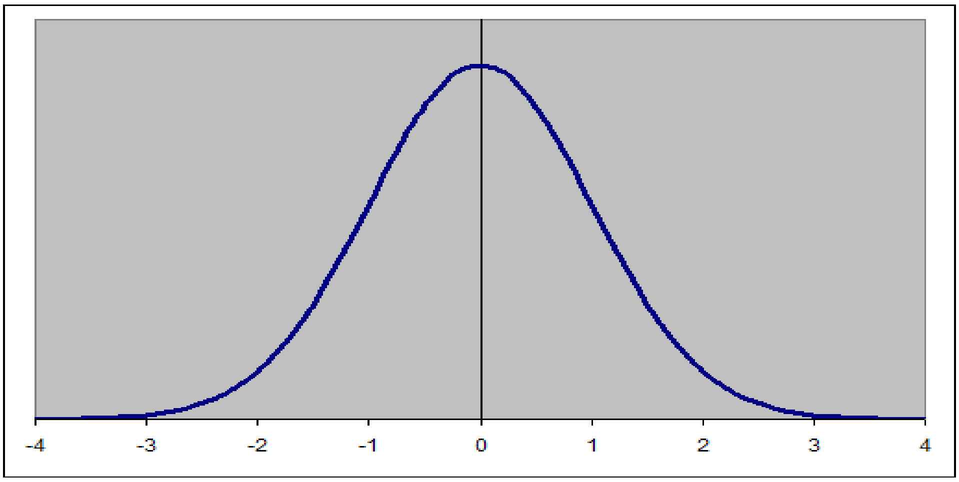

Figure 6: Normal standard deviation diagram.

5.2 Mean-Square Deviation

Assuming $y_1, y_2, y_3, \ldots\ldots\ldots. y_n$ are n data points, the MSD for it can be computed as

$$MSD = \frac{\sum(Y_i - Y_0)^2}{n} = \frac{(Y_1 - Y_0)^2 + (Y_2 - Y_0)^2 + (Y_3 - Y_0)^2 + K}{n} \quad [3]$$

It can also be shown that

$$MSD = \sigma^2 + (Y_{avg} - Y_0)^2 \quad [4]$$

Where, Y_0 is the target value and σ is the standard deviation (population, using n as the divisor).

MSD can be seen as deviation with respect to the origin. For the fact that like other forms of deviations, MSD is always preferred to be a smaller quantity in all three quality characteristic, in case of bigger quality characteristics, the inverse of the deviation squares are used as shown below. In this way, despite the quality characteristics of the original results, the desirability of MSD are always retained as smaller is better.

$$\text{Nominal: } MSD = \frac{(Y_1 - Y_0)^2 + (Y_2 - Y_0)^2 + (Y_3 - Y_0)^2 + (Y_i - Y_0)^2}{n} \quad [5]$$

$$\text{Smaller: } MSD = \frac{Y_1^2 + Y_2^2 + Y_3^2 + K}{n} \quad [6]$$

$$\text{Bigger: } MSD = \frac{1/Y_1^2 + 1/Y_2^2 + 1/Y_3^2 + K}{n} \quad [7]$$

5.3 Percentage Variation

Assuming that y_1 and y_2 is a pair of data, the percentage variation between them will be expressed by equation 4.8;

$$\text{Percentage variation} = \frac{y_1 - y_2}{y_1} \times 100\% \quad [8]$$

For the purpose of this project analysis, standard deviation and percentage variation were used to ascertain the level of variability at different levels of performance. While standard deviation was used to study the variation at the location level, a more in-depth study of variation was conducted at the region level using percentage variation.

5.4 Applying standard deviation

By applying equation 2 to the results,

$$\sigma = \sqrt{\frac{(x_1 - \mu)^2 + (x_2 - \mu)^2 + \cdots + (x_N - \mu)^2}{N}},$$

The results for 15˚C at 24 hours, we have that;

$$\mu = \frac{89.85 + 106 + 113.3 + 104.3}{4} = 103.36$$

$\mu = 103.36$

$(89.85 - 103.36)^2 = (-13.51)^2 = 182.52$

$(106 - 103.36)^2 = (2.64)^2 = 6.97$

$(113.3 - 103.36)^2 = (9.94)^2 = 98.80$

$(104.3 - 103.36)^2 = (0.94)^2 = 0.88$

$$\sigma^2 = \sqrt{\frac{(-13.5)^2 + (2.64)^2 + (9.94)^2 + (0.94)^2}{4}}$$

$$\text{Therefore, } \sigma = \sqrt{\frac{182.52 + 6.97 + 98.80 + 0.88}{4}}$$

$\sigma = \sqrt{72.29} = 8.5$

This means that for the lead-free solder paste aged prior to printing at 15˚C for 24 hours, the standard deviation (σ), of the printed deposits for location 1 is equal to 8.5. The same process was used to compute the standard deviation of all the locations measured for both P 1 and P 2. The computed results are shown in table 5.

Table 5: Result of standard deviation for LF318 (P 1) and LF328 (P 2).

Temperature (˚C)	Time (Hours)	Standard deviation (P 1)		Standard deviation (P 2)	
		Location 1	Location 2	Location 1	Location 2
15	24	8.5	9.9	8.9	7.6
15	48	4.0	5.2	9.2	6.1
15	72	12.2	3.7	9	3.8
25	24	10.4	8.1	5.3	5
25	48	7.6	6.1	6.6	8.6
25	72	12.3	3.7	7.4	6.9
35	24	8.7	8.6	13.1	2.9
35	48	8.6	1.9	8.8	6
35	72	13.4	1.2	12.6	1.8

From table 5, it can be seen that the lowest standard deviation is at (P 1), location 2 of the paste aged at 35˚C for 72 hours. This means that the solder paste deposits tend to be very close to the mean. In other words, the printing was able to produce a normal distribution at this location, which means that most of the apertures in that particular location had deposits that are close to its average.

Generally, location 2 seems to have a normal distribution than location 1. This is most likely because the aperture sizes at location 2 are larger than that of location 1, therefore enabling the squeegee to deposit more solder paste at a balanced level.

5.5 Applying Percentage variation

For P1 location 1, region 1, the percentage variation was calculated as

$$\% \text{ variation} = \frac{93.2 - 86.5 \times 100}{93.2} = 7.2\%$$

The same procedure was used to calculate for all the regions measured.

Table 6: Percentage variation result of deposited solder paste height for LF318.

Location	Region	Time (Hours)	Percentage variation (%) for P1		
			15˚C	25˚C	35˚C
Loc 1	1	24	7.2	- 0.8	5.2
	2	24	- 10.7	1.2	10.4
	3	24	8.6	18.0	1.6
	4	24	16.2	- 11	4.1
Loc2	5	24	3.4	4.0	17.0
	6	24	9.5	7.9	5.9
	7	24	2.6	- 5.2	11.0
	8	24	4.3	5.7	19.3
Loc 1	1	48	8.9	5.2	- 0.6
	2	48	3.3	8.8	4.6
	3	48	7.5	1.1	- 2.2
	4	48	1.2	3.7	4.5
Loc 2	5	48	1.2	- 2.2	20.0
	6	48	13.8	8.9	- 4.2
	7	48	16.7	- 2.5	14.1
	8	48	8.3	13.6	11.1
Loc 1	1	72	5.3	- 0.1	0.1
	2	72	24.2	6.6	4.9
	3	72	14.8	1.7	2.0
	4	72	- 3.3	7.1	8.9
Loc 2	5	72	3.6	17.3	6.9
	6	72	15.0	18.0	3.1
	7	72	4.5	7.4	11.3
	8	72	20.5	7.8	13.6

Table 7: Percentage variation result of deposited solder paste height for LF328

Location	Region	Time (Hours)	Percentage variation (%) for P2		
			15˚C	25˚C	35˚C
Loc 1	1	24	18	10.5	0.2
	2	24	5.1	3.9	- 5.0
	3	24	13.3	- 4.9	8.8
	4	24	4.8	- 3.3	27.8
Loc 2	5	24	4.6	6.7	8.2
	6	24	0.4	19	10.3
	7	24	- 6.9	5.1	19.7
	8	24	3.3	9.1	14.4
Loc 1	1	48	5.1	0	7.6
	2	48	4.4	- 4.8	10.6
	3	48	9.5	5.3	4.9
	4	48	29.4	1.9	4.3
Loc 2	5	48	10.6	8.1	18.9
	6	48	8.7	2.0	9.5
	7	48	- 5.8	2.2	3.6
	8	48	0.7	14.2	9.1
Loc 1	1	72	3.6	0.5	12.3
	2	72	7.6	11	6.1
	3	72	3.4	1.3	- 6.8
	4	72	3.3	3.9	13.3
Loc 2	5	72	5	10.6	- 14.4
	6	72	13.4	16	- 6.7
	7	72	4.7	11.5	- 4.0
	8	72	16.5	3.9	3.7

According to Prasad (1997), the maximum allowable variation in paste height should be about 20%. Figures 7 (a –f) shows the graph of the percentage variation.

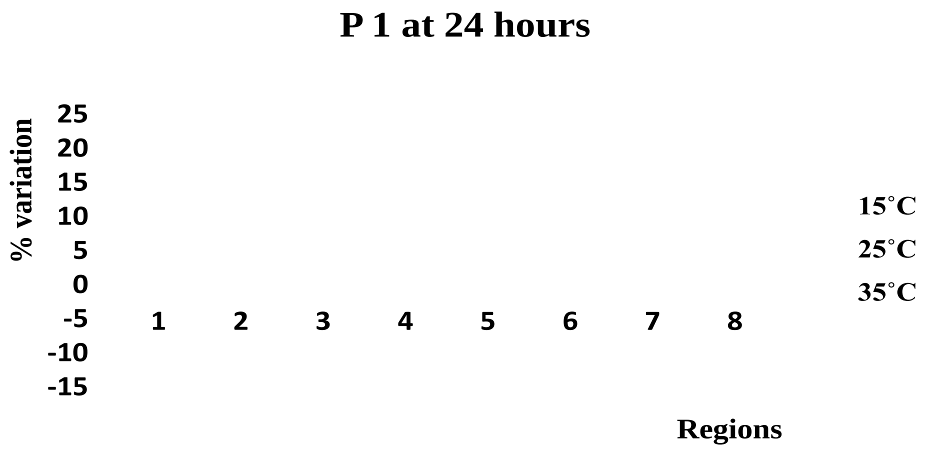

Figure 7(a): Percentage variation plot for P1 at 24 hours

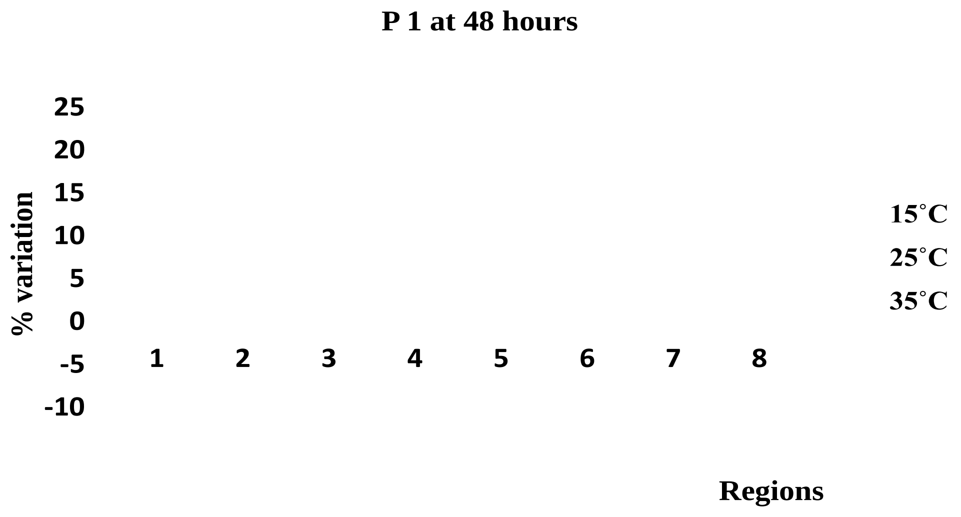

Figure 7(b): Percentage variation plot for P1 at 48 hours

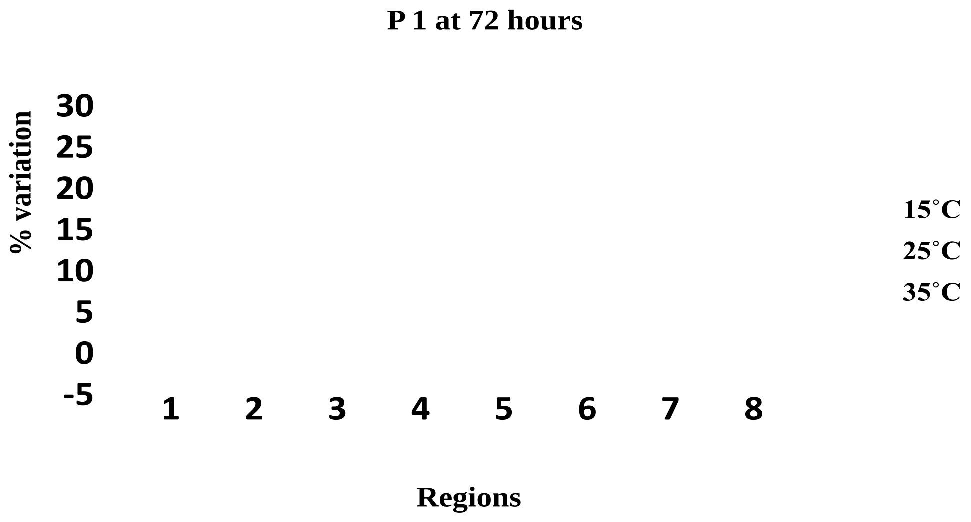

Figure 7(c): Percentage variation plot for P1 at 72 hours

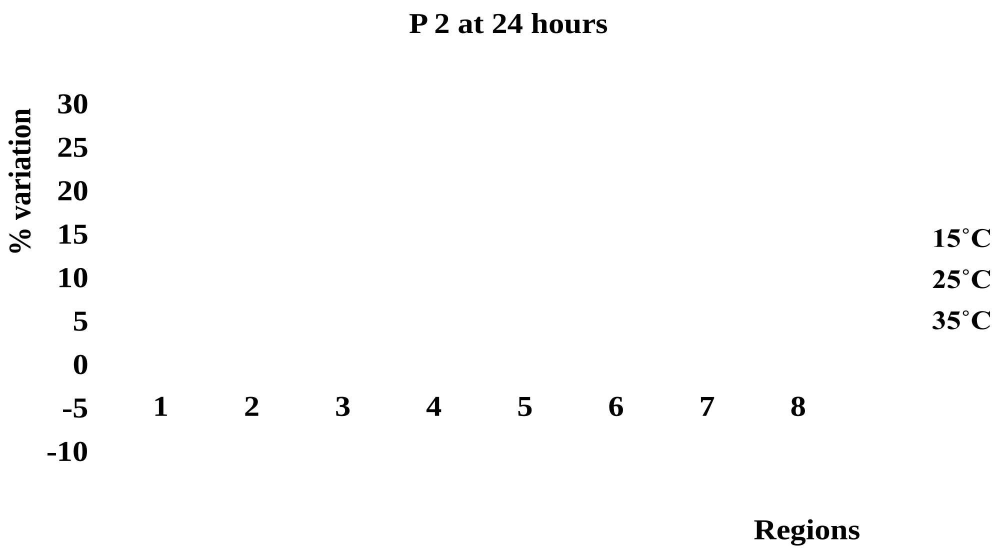

Figure 7(d): Percentage variation plot for P2 at 24 hours

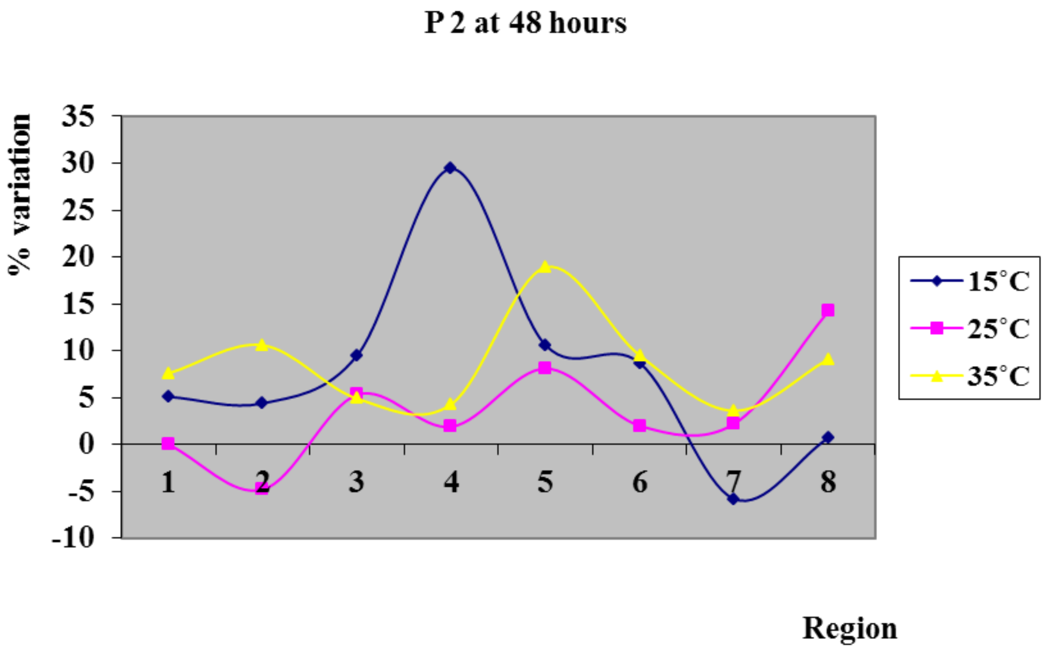

Figure 7(e): Percentage variation plot for P2 at 48 hours

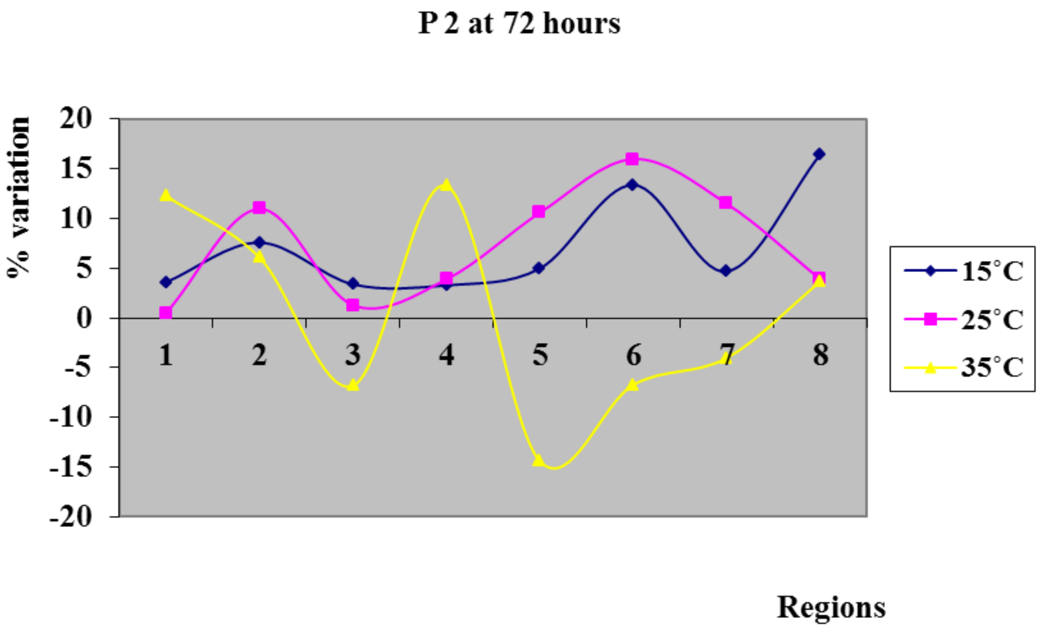

Figure 7(f): Percentage variation plot for P2 at 72 hours

Since 20% is the maximum allowable percentage variation, upper control limit (UCL) and lower control limit (LCL) was set at 20% and -20% respectively for this experiment. Therefore, these control limits was used to check for out of control conditions in the printing process. For the whole process/experiment, only four out of control conditions (freak) were found at the region which is an infinitesimal part of the deposits.

VI. Slump Test Results

Lee (2002) stated that slump is a phenomenon where the paste viscosity is not high enough to resist the collapsing force exerted by gravity, and consequently results in spreading beyond the area to be deposited. Cold slump was used to determine the solder paste behaviour. Cold slump refers to the slumping behaviour at room temperature while hot slump refers to slumping during reflow. Figure 8 shows the slump location that was visually observed using a Leica S6D zoom stereomicroscope. From the observations, paste stored at 35˚C had the highest level of slumping.

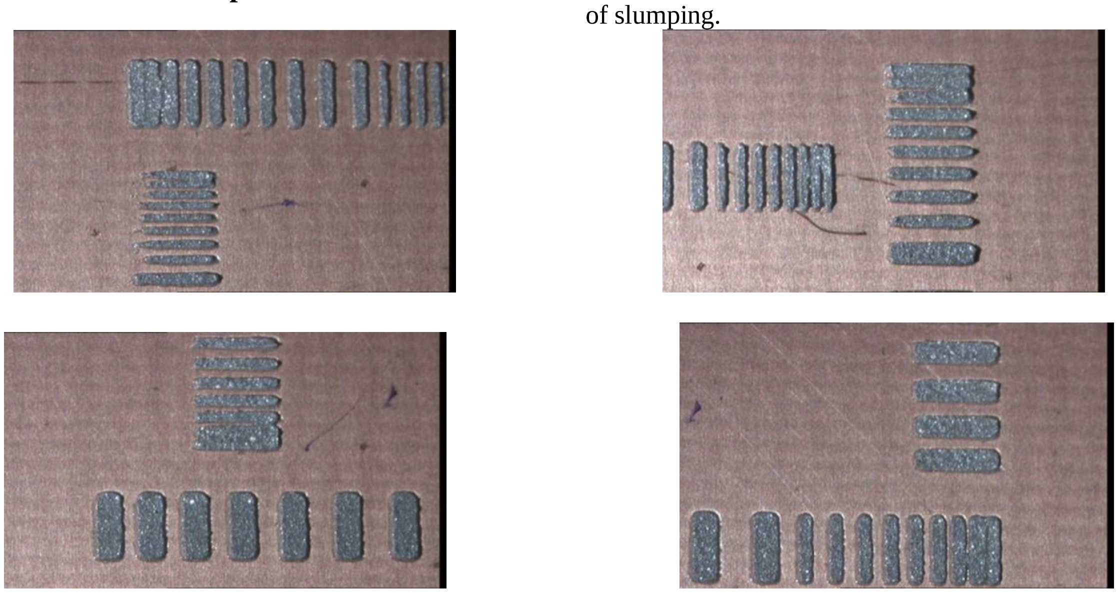

Figure 8: Four edges of the slump location for P1

VII. Conclusion

From the measured heights of the solder paste deposit, the paste stored at 35˚C for 72 hours, produced the height closest to the target. However, it was found that a lot of slumping occurred, making it unfavourable. Though more slumping occurred for the paste stored at 35˚C, it was not enough to get the height lower than that stored at 25˚C or 15˚C. Because of slumping behaviour of solder paste, it was believed that the height of the solder paste would decrease as the temperature increased. This was not exactly the case, the height rather increased slightly as the temperature increased.

This behaviour was as a result of some factors. First, paste was not able to role at low temperatures such 15˚C. Secondly, as the temperature increased, the paste rolled and was able to fill the apertures effectively. Therefore, considering this slumping phenomenon, the paste stored at 25˚C for 48 hours produced the best results of good height with minimal slumping. Analysis shows that variability of the paste distribution was lowest and more uniform for paste stored at 25˚C for 48 hours. The percentage variation showed zero variation in one of the regions for P2. With the results of the variability analysis, 25˚C showed less variability. From the analysis, it is obvious that temperature has tremendous effects on the printing performance of solder paste. This study recommends 25˚C as a good temperature for solder paste printing.

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