

OPTIMIZATION OF SOLDER PASTE PRINTING PARAMETERS USING DESIGN OF EXPERIMENTS (DOE)

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Abstract. The solder paste printing process is an important process in the assembly of Surface Mount Technology (SMT) devices using the reflow soldering technique. There is a wide agreement in the industry that the paste printing process accounts for the majority of assembly defects. Experience with this process has shown that typically over 60% of all soldering defects are due to problems associated with the screening process. Therefore, operation and parameter setup of the stencil printing process are the key elements when trying to minimize defects. Parameters such as squeegee pressure, squeegee speed, stencil separation speed, snap-off and stencil cleaning interval are the most important factors in the process to achieve a better yield. This paper describes the experiment design approach for solder paste printing process. A factorial design technique has been used to study the effects of the solder paste printing process parameters. Sixteen experimental trial were carried out in the experiment with two levels for each factor. The output from the experiment is the solder paste height, and the data has been statistically analyzed by using Minitab Software. The Analysis of Variance (ANOVA) showed that the important factors for the solder paste height are squeegee pressure and snap-off with the optimal setting for printing speed, squeegee pressure, snap-off, squeegee separation, and cleaning interval. The experiment error between the predicted regression model and actual verification was found to be 1.61%. It is shown that by using DOE 18% improvement of the solder paste height can be achieved.

Keywords: Design of experiments, solder paste printing, Analysis of Variance (ANOVA), regression analysis

Abstrak. Proses mencetak timah merupakan satu proses yang penting dalam pemasangan perkakasan *Surface Mount Technology* (SMT) menggunakan teknik pencetakan *reflow*. Terdapat satu persetujuan global di dalam industri di mana proses pencetakan timah melibatkan sebahagian besar kecacatan disebabkan oleh proses pencetakan. Pengalaman dengan proses ini telah menunjukkan bahawa lebih 60% daripada keseluruhan kecacatan pencetakan adalah bergantung kepada masalah yang berlaku pada proses *screening*. Walau bagaimanapun, operasi dan pemilihan parameter bagi proses pencetakan timah merupakan elemen utama dalam usaha bagi meminimumkan kadar kecacatan tersebut. Parameter seperti tekanan *squeegee*, kelajuan *squeegee*, kelajuan pemisahan *stencil*, *snap-off* dan sela masa pembersihan stencil merupakan faktor penting dalam proses bagi mencapai keluaran yang lebih baik. Kertas kerja ini menerangkan pendekatan reka bentuk eksperimen bagi proses pencetakan timah. Teknik reka bentuk faktorial digunakan bagi mengkaji kesan parameter proses pencetakan timah. Sebanyak 16 eksperimen telah dijalankan dengan dua tahap bagi setiap faktor. Hasil daripada eksperimen yang dijalankan adalah ketinggian pencetakan timah, dan data telah dianalisis secara statistik menggunakan perisian Minitab. Analisis

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varians menunjukkan bahawa faktor yang penting bagi ketinggian pencetakan timah ialah tekanan *squeegee* dan *snap-off* dengan menetapkan kelajuan pencetakan, tekanan *squeegee*, *snap-off*, pengasingan *squeegee* dan sela pembersihan pada tahap optimum. Ralat eksperimen antara model regresi dan pengesahan sebenar ialah sebanyak 1.61% Penggunaan DOE menunjukkan 18% pembaikan ketinggian pencetakan timah boleh dicapai.

Kata kunci: Reka bentuk eksperimen, pencetak timah, analisa varians, analisa regresi

1.0 INTRODUCTION

Surface mount technology (SMT) is used extensively in the electronics industry. Surface-mounted components are often smaller than their leaded counterparts, and potentially more reliable products can be designed and manufactured using SMT. The solder paste stencil printing process is a very critical step in the surface-mount manufacturing process [1, 2]. Experience has shown that typically over 60% of all soldering defects are due to problems associated with the screening process [3, 4]. Therefore, operation and setup of the stencil printing process are key elements to be considered when trying to minimize defects [5, 6]. The main reason for printing solder paste onto the Print Circuit Board (PCB) is to supply solder alloy for the solder joints. To achieve this objective, the solder paste print must be aligned correctly, the correct amount of solder paste for each joint must be present and the print should form an even layer of paste for perfect component placement [7, 8]. The solder paste on top of the stencil is partly rolled and pressed into the stencil apertures and onto the PCB solder lands by a moving and angled squeegee. The squeegee angle must be between 45 to 60 degree (usually not adjustable) and the rolling solder paste should have a diameter of 15 to 20 millimeter for optimum conditions. As a main rule, thin steel squeegee should be used for metal stencils and as hard as possible squeegee, for mesh stencils. Rubber squeegee used on stainless steel stencils will wear out quickly and cause severe scooping in large apertures. Steel squeegee used on mesh stencils will damage the mesh after only few prints [9-11]. The squeegee printing edge must be sharp to secure a well-defined print. When using an old worn out squeegee with rounded printing edge, the squeegee angle is reduced and the solder paste will not roll as desired [12, 13]. Using the appropriate stencil printing parameters is important to obtain a good result when printing solder paste onto PCBs. The parameters, squeegee pressure, printing speed, snap-off, separation speed and stencil cleaning are explained below. Solder paste printing in the surface mount industry has come a long way in the past fifteen years. Initially, 50 mil pitch devices already presented a problem in high defect rate. Now, as packages shrink in size and increase in lead count, we see the same problem of very high defect rates (100 to 200 PPM) on 20-mil pitch and below while manufacturing sees six sigma quality rates on larger pitch components [12, 14, 15]. The main sources for solder paste stencil printing process defects are stencil, environment, solder paste, and stencil printing parameter [13, 16].

2.0 DETAILS OF PROCESS PARAMETERS

2.1 Stencil

Metal stencils can be made of different materials. Besides stainless steel, they can be made of copper, bronze, or nickel. There are 3 different metal stencil-manufacturing methods: Etching, electroforming and laser cutting. The apertures in both laser-cut and electroformed stencils have very sharp edges and are slightly conic. This makes the solder paste slip easily off the aperture edges and thereby secures a uniform print. The metal stencils are attached to the printing frame using tensioned mesh or directly using a special frame with gripping systems, which can easily damage the stencils and thereby resulting in poor printing quality. The thickness of the metal stencil is typically 150 microns but 100, 125 and 200 microns are also available. The thickness should be chosen based on the job in hand. For very fine pitch such as 0.3 mm lead pitch, 100 or 125-micron stencils could be used and for lead pitch down to 0.5 mm, 150-micron stencils can be used. The stencil thickness together with the aperture size also determines the amount of solder paste present to form each solder joint during reflow soldering. As a guideline, the minimum stencil aperture width must be at least 3 times (preferable 5 times) the diameter of the largest solder particle and the stencil aperture width should also be larger than the stencil thickness. Rounded aperture corners will reduce clogging of fine pitch apertures and smearing. The top surface of the metal stencil should be slightly roughened to achieve a perfect solder paste roll during printing.

2.2 Environment

Dust and dirt from the air that ends up on the PCBs and stencils can cause defects such as bridging and poor wet-ability in the reflow soldering process. A small piece of fibre or hair between two fine pitch solder pads can easily cause bridging. It is therefore very important that the PCBs are stored in sealed packages and if necessary, cleaned before use. Air draught in the production area can speed up evaporation of the solvents in the solder paste and thereby makes the solder paste dry out. High temperature can also make the solder paste dry out quickly. If the room temperature in the production area varies a lot, it will be very difficult to control the printing process. The viscosity of the solder paste changes with the temperature and the solder paste print will sometimes be perfected and at other times, paste will slump and result in bridging. The temperature window is between 21 – 25°C.

2.3 Solder Paste

Several paste characteristics must be carefully controlled to achieve optimum production results. These include: percent of metal, viscosity, slump, solder balls, flux activity working life and shelf life.

2.4 Stencil Printing Parameters

Stencil Printing Parameters are the most important factors in the solder paste printing process to achieve better yield. The first parameter is the squeegee pressure. It should be as low as possible to scrape the stencil clean of solder paste particles when printing. The amount of pressure is determined by the printing speed and stencil type. The printing speed is usually recommended by paste manufacturer.

Usually the solder paste manufacturer only gives guideline to the right printing speed: typically between 20 and 80 mm per second. The printing speed is a major factor in the printing cycle time and therefore, important as it can compromise the print quality. Snap off is the distance between the stencil underside and the PCB placed in print position but without the squeegee touching the stencil. For metal stencil printing, the snap off should be zero and also called contact printing. For mesh screen-printing, the snap off should be set to between 0.5 and 3.0 mm. A high snap off will result in a thicker layer of solder paste. The speed of separation between stencil and PCB after printing is important. A too rapid separation speed when printing fine pitch will result in clogging of the stencil apertures. It will also result in tailing and formation high of edges around the solder paste deposits. In general, if all printing parameters are in control, stencil underside cleaning is not necessary. Cleaning can be done either manually or automatically. The wiper does not clean the stencils underside but simply move the solder paste particles from around the apertures to the complete stencils underside. Stencil cleaning prior to use is important to prevent dust and dirt from entering the solder joints.

3.0 EXPERIMENT DESIGN AND RESULT ANALYSIS

3.1 Experimental Design Steps

The DOE steps are defined as identifying the response or output, identifying factors for the study, determination of factor levels and range of factor setting, choice of appropriate experimental design, run the experiment, collect and analyze the data, draw conclusion and act on the results [17-21]. These steps can be summarized and we used the following strategy in designing, performing and analyzing experiment. One of the complete factorial experiment is 2^k factorial designs; k is the number of factors investigated at two levels. In order to calculate the number of runs, e.g. if $k = 5$ then the number of runs is $2^5 = 32$ runs. The number of run increases as the k value increases. In order to reduce the number of experimental runs, fractional factorial was introduced which used only a fraction of the total possible combinations of levels. The number of run is given by 2^{k-1} , e.g. if $k = 5$, $2^{5-1} = 2^4 = 16$ experimental runs. A team of engineers, operators, and statisticians was formed to collaborate on a unified objective for the study, and determine a list of factors that might influence

both the average amount of solder paste applied and the process variability. This cross-functional team selected five factors for the screening experiment. They also decided to use two levels for each factor. The five factors chosen and their actual low and high levels are as follows:

- A* – Squeegee pressure; levels (4 and 7 kg).
- B* – Squeegee speed; levels (30 and 60 mm/s).
- C* – Snap off; levels (-0.1 and 0.1 mm).
- D* – Separation speed; levels (1 and 5 mm/s).
- E* – Cleaning internal (Stroke) (5 and 10)

The team also identified two potential nuisance factors; temperature and humidity. It was felt that large variation in these factors could potentially adversely affect the experimental results. Therefore, the team decided to hold these factors constant during the experiment. Although the factors are controlled, the team directed close attention to the results for any potential influence. The response is the height of solder paste. The experimental design selected was a one-half fraction of a 2^{5-1} design. The defining relation for this design is $I = ABCDE$. Consequently, every main effect is aliased with a four-factor interaction, and every two-factor interaction is aliased with three-factor interaction. Thus, the design is of resolution V. The design provides good information concerning the main effects and two-factor interactions.

3.2 Data Analysis

The results of the experiments are analysed in the following section.

3.2.1 Analysis of Variance (ANOVA)

The following section describes the results for the dependent variable (response) solder paste height in mils. The analysis performed is an Analysis of Variance “ANOVA” Model that identifies the amount of experimental error and the significance of the model in accounting for the variability in the experiment. The test identifies the factors and interactions that are significant. Effect listed as “most significant” represent the independent process variables that have the greatest influence on a particular treatment response. The important factors are graphically displayed using main effect plots, such as effect pareto on solder paste height and interaction plots (Figures 1 and 2).

The pareto chart was developed to compare the relative magnitude and significance of both main and interaction effects. Minitab plots the effects in decreasing order of the absolute value of standardized effects and draws a reference line on the chart.

Pareto chart of the standardized effects
(response is SolderHt, Alpha = .10)

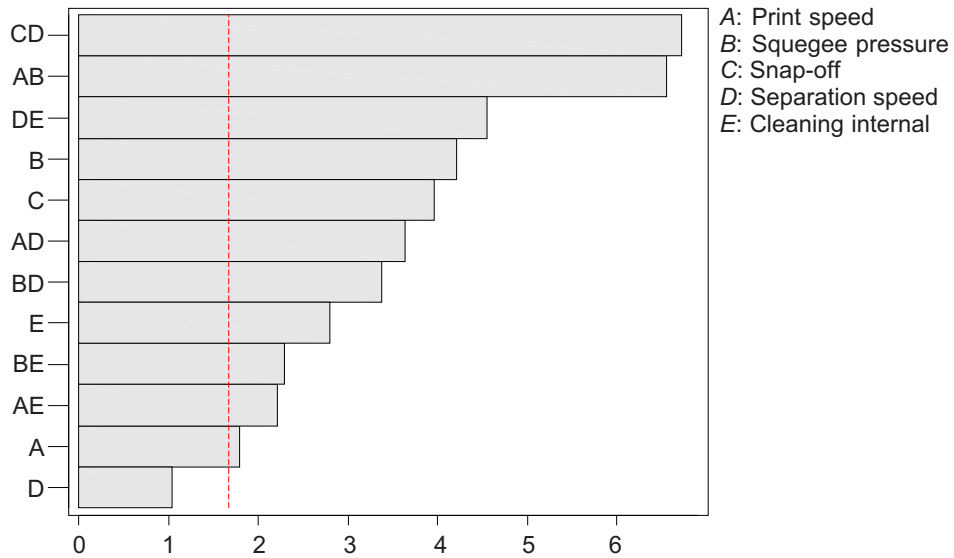


Figure 1 Effect pareto on solder paste height

Interaction plot (data means) for SolderHt

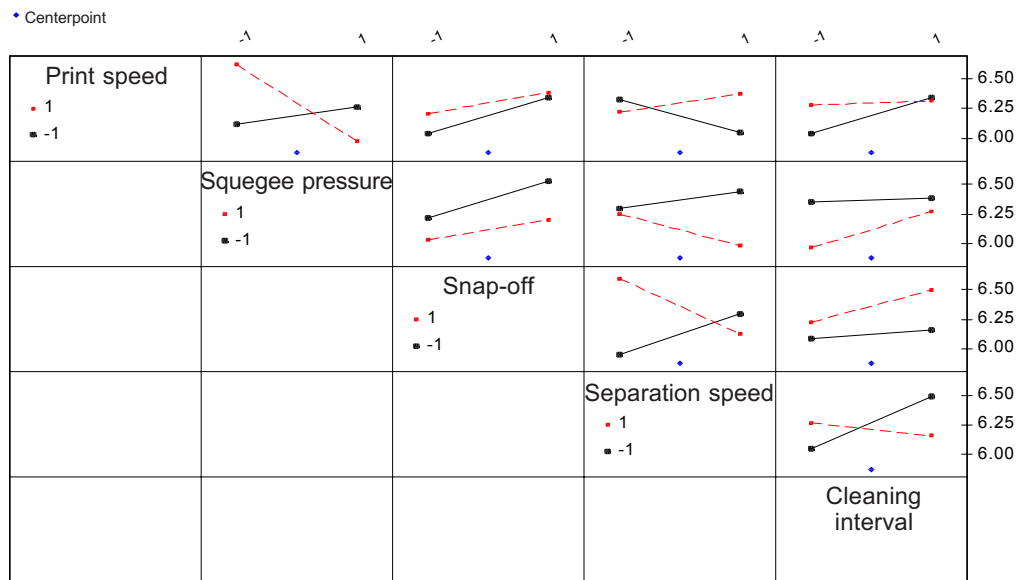


Figure 2 Interaction plot for solder paste height

Any effect that extends past the reference line is considered significant. The 3 largest dominant factors are:

- (i) *CD* Interaction: Snap off \times Separation speed
- (ii) *AB* Interaction: Print speed \times Squeegee pressure
- (iii) *DE* Interaction: Separation speed \times Cleaning interval

Interaction plot was used to determine if two factors interact in their effect on the response and compare the relative strength of the effects. An analysis of variance (ANOVA) conducted for the response of the parameters, provided assurance that each of the initially selected effects was statistically significant. In some cases, a variable was not significant at the traditional 0.05 level, but was retained in the model because it was involved in an interaction. Figure 2 summarizes the results from the ANOVA where cells containing the symbol “1” identify factors having the strongest effects and cells containing the symbol “5” identify factors having the smallest effects. The normal probability plots of residual for each response is satisfactory. From the main effect plot, the optimal parameters to a better solder paste height parameters for each factor may be known. For the response solder paste height, the smallest value is considered as the best result.

3.3 Optimal Setting

From the data that has been analyzed, the optimal setting for solder paste printing process was obtained. The optimal setting was as follows:

- A* – Printing speed (60 mm/s).
- B* – Squeegee pressure (7 kg).
- C* – Snap off (-0.1 mm).
- D* – Separation speed (1 mm/s).
- E* – Cleaning interval (5 Internal).

3.4 Verification and Validity

For verification experiment, five runs were carried out. So, there are five replication for this verification experiment. The response solder paste height of the verification experiment was also measured by using the Cyberoptics Cyberscan 200. After the measurement, the resulted solder paste height was collected and shown in Table 1.

In Table 1, R1 refer to “Replicate 1”, R2 refer to “Replicate 2”, R3 refer to “Replicate 3”, R4 refer to “Replicate 4” and R5 refer to “Replicate 5”. The average of the verification data experiment is 5.68 mm. The average of the verification result was the actual value and the regression model (\hat{y}) was the predict value. Since the

Table 1 Result of verification experiment for response solder paste height

	Unit (mils)
R1	5.8
R2	5.6
R3	5.7
R4	5.7
R5	5.6
Average	5.68

% of error is small, this result is valid. The optimize setting can be used to the solder paste printing process for the model SB0350. To calculate the percentage of improvement, first five solder paste thickness data before the experiment were chosen. Then, the average of the data was calculated. The data that has been chosen are shown in Table 2.

From Table 2, the average of the five worst flatness data from the experiment result is 6.75 mils. So the percent improvement can be calculated as:

$$\% \text{ improvement} = [(6.78 - 5.68) / 5.68] \times 100 \% = 18 \%$$

Table 2 Five worst data of solder paste height from experiment result (Response - solder paste, height (mm))

Data	
1	6.28
2	6.9
3	7.22
4	6.48
5	6.86
Average	6.75

4.0 CONCLUSION

This paper has discussed an application of the Design of Experiment (DOE) $\frac{1}{2}$ fraction for optimizing the solder paste printing process. Fractional factorial designs are useful in factor screening because they reduce the number of runs to a manageable

size. The runs that are performed are a selected or fraction of the full factorial design. As shown in this study, the DOE are often carried out in four phases: planning, screening (also called process characterization), optimization, and verification. Well-designed experiments can produce significantly more information and often require fewer runs than haphazard or unplanned experiments. In addition, a well-designed experiment will ensure that we can evaluate the effects that have been identified as important. In this case study, we can summarize that the DOE provides a systematic and efficient methodology for design optimization of the solder paste printing process with far less effort than would be required for most optimization techniques. At the end of this study, it was found the optimal setting for solder paste printing process are high squeegee pressure, high printing speed, low snap-off, low separation speed and low cleaning interval. These optimal setting results in a small value of response solder paste height after the verification run was conducted. It was found that the percentage between the predicted and actual experiment is 1.16%. This is very small and so the experiment is considered valid. From calculation, it was found that, by using the classical method of DOE, 20% improvement was achieved. The cycle time for the printing process can also be minimized by increasing of the speed of separation and maximizing the cleaning interval.

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