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ORIGINAL ARTICLE

J. P. C. Tong · F. Tsung · B. P. C. Yen

A DMAIC approach to printed circuit board quality improvement

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Abstract Since the early 1990s, six sigma has been sweeping the business world, driving greater manufacturing and service quality than has ever been seen before. Statistical quality techniques are one of the decisive factors contributing to the success of the six-sigma implementation. Applying statistical quality techniques is especially important in the manufacture of surface-mounted printed circuit boards (PCB). As any defect in the solder joint can lead to circuit failure, the screening process is regarded as the most critical process in PCB manufacturing. According to the current process capability study of a PCB company, the capability of the screening process is under 1.33—the company requirement. That is to say, the current printing process cannot reach a four-sigma level. Therefore, the objective of this study is to improve the sigma level of the screening process through the define-measure-analyse-improve-control (DMAIC) approach. At the early stages, process capability analysis (PCA) and statistical process control (SPC) were used to measure and analyse the current printing performance of the screening machines. During later stages, design of experiment (DOE) was conducted to determine the optimal settings of the critical-to-quality factors in the screening process. By using these optimal settings, six-sigma performance can be achieved.

Keywords Six sigma improvement · Define-measure-analyse-improve control (DMAIC) approach · Design of experiment (DOE) · Multi-layer printed circuit board (PCB) · Surface mount technology (SMT) · Screening process

J. P. C. Tong · F. Tsung (✉)
Department of Industrial Engineering
and Engineering Management,
The Hong Kong University of Science
and Technology, Hong Kong, PR China
E-mail: season@ust.hk

B. P. C. Yen
School of Business,
The University of Hong Kong,
Hong Kong, PR China

1 Introduction

Since the early 1990s, six sigma has been initiated using statistical tools and techniques in business, transactional, and manufacturing processes. It has been proven to be successful in reducing costs, improving cycle times, eliminating defects, raising customer satisfaction, and significantly increasing profitability. The effectiveness of six sigma to a large extent depends on its statistical techniques of defining, measuring, analysing, improving, and controlling the critical processes. Here, a case study on six-sigma quality improvement of printed circuit board (PCB) through the DMAIC approach is presented.

Nowadays, the market demands increasingly complex electronic products in terms of specifications. The circuitry of a PCB is becoming more and more sophisticated. Therefore, quality excellence is very important in the manufacture of surface-mounted PCBs. From the company's point of view, the screening process is the most critical process that can affect the PCB quality. Without proper control of the screening process, common printing problems such as bridging, smeared paste, short circuit, misregistration, and open circuits can occur [1]. According to the current process capability study, the sigma level of the screening process was not very satisfactory. Therefore, a study was conducted in the screening process with the objective of improving the sigma level for a series of product called PSSD.

This study was conducted in reference to the DMAIC approach. After the specific problem in PSSD was identified and defined, process capability analysis (PCA) and statistical process control (SPC) were used to measure and analyse the current printing performance. Design of experiment (DOE) was then conducted to improve the sigma level of the screening process by determining the optimal settings. Initial experiments were conducted to screen out the factors that might have influence on the printing performance. Afterwards, further experiments were used to determine the optimal settings of the significant factors. By using these optimal settings, the printing performance can be improved and therefore the sigma level of the screening process can also be enhanced. Finally, some control strategies were recommended in reference to the experimental findings in order to sustain the improvement of the sigma level.

The remainder of the paper is organised as follows: Section 2 offers the background information about the company and the screening process, and defines the problem of initiating DMAIC. Section 3 presents the DMAIC approach in this study. Section 4 describes the details of the initial experiments and the further experiments. Section 5 presents the recommended control strategy and the predicted performance after using the optimal settings. Finally, Section 6 concludes by summarising the contribution of this study and offering suggestions for future research.

2 Company and process background

This case study was conducted in an electronic company located at an industrial park in southern China. The company manufactures multi-layer PCBs using surface mount technology (SMT), which is a technique of placing surface mount devices (SMDs) on the surface of a PCB. SMDs are micro-miniature leaded or leadless electronic components that are soldered directly to the pads on the surface of the PCB. The major manufacturing processes in the company are solder screen, component placement, and solder reflow. As any defect in any of the solder joints can lead to failure of the circuit, the screening process is regarded as the most critical process in PCB manufacturing.

The screening process is a manufacturing process that transfers solder paste onto the solder pad of a PCB. The application method of solder paste is printing and the printing technique used is off-contact printing in which there is a snap-off distance between a stencil and a PCB. The type of screening machine used to manufacture PSSD products is semi-automatic. As the squeegee system consists of the front and back blades, there are two types of printing, front printing and back printing, as shown in Fig. 1. In current practice, both front and back printing are used alternatively during printing.

During a printing process, two PCBs are placed side-by-side on the holder of a screening machine as shown in Fig. 1. The solder paste is then manually placed onto a stencil before printing. The front/back blade makes line contact with the stencil and close contact with the given amount of solder paste. The solder paste is then rolled in front of the front / back blade. In this way, solder paste is pressed against the stencil and transferred onto the solder pad through the stencil openings. The operation of a screening machine is shown in Fig. 2.

3 Five phases of the Six-Sigma approach

The five core phases of the six-sigma approach are define, measure, analyse, improve, and control. Therefore, the six-sigma approach is also referred to as the DMAIC

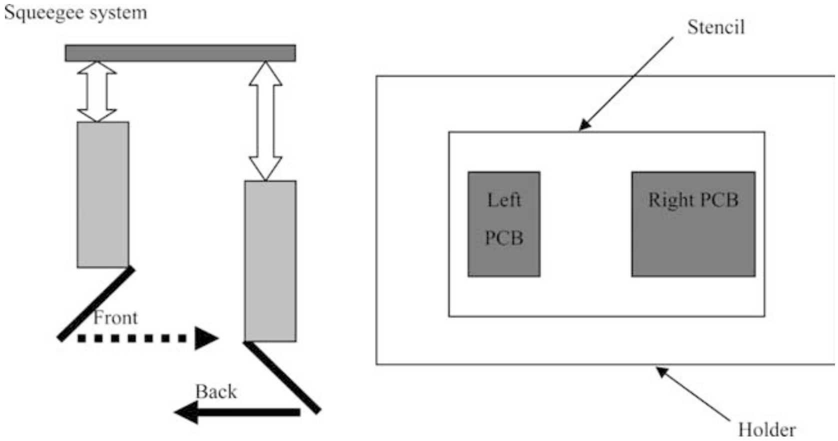

Fig. 1 The two printing types and two sides on the holder

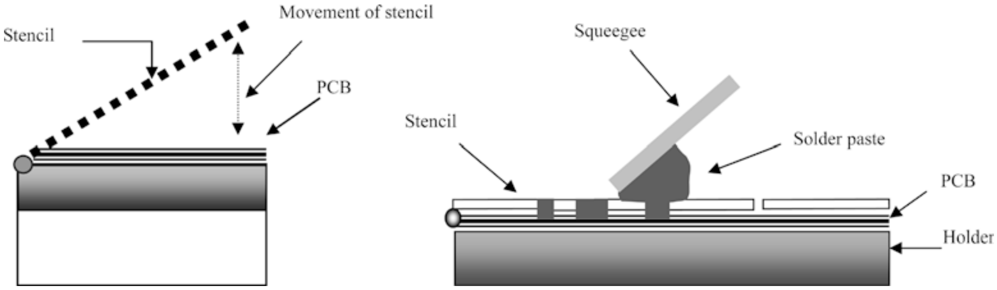

Fig. 2 The operation of a screening machine

approach. The details of these phases are as follows [2]: In the define phase, the specific problem is identified, and the project goals and deliverables are defined. In the measure phase**,** a review of the types of measurement systems and their key features is included. The nature and properties of data collection must be thoroughly understood by companies. In the analyse phase, specific statistical methods and tools are used to isolate the key pieces of information that are important to explaining the number of defects. In the improve phase, the key factors that cause the problem are discovered. In the control phase, the processes that create the product or service are controlled and monitored continuously in order to ensure that the problem will not occur again. The details of the DMAIC approach of this case study are as follows:

3.1 Define phase

This project specifically focuses on improvement of the sigma level of the PCB screening process. In the screening process, the solder paste volume (height) transferred onto the PCB is the most important factor that needs to be controlled carefully. This is because too little solder paste can cause open circuits and too much solder paste can cause bridging between solder pads in the subsequent processes. As a result, the solder paste height on the solder pads is identified as a critical-to-quality (CTQ) characteristic that needs to be controlled in a very precise way by the company.

3.2 Measure phase

To control the screening process, the quality team in the company has asked operators to measure the solder paste height for the PSSD product on five different points on a PCB. The locations of the 5-point measurements are shown in Fig. 3 and include: two points in the U1 location, two points in the U2 location and one point in the J1 location. The solder paste height on five PCBs is measured using the Cyberoptics Cybersentry system every four hours. The gage repeatability and reproducibility (R&R) of the measurement system was verified before the study on the solder paste height was conducted. The operators then recorded the solder paste height in the SPC data record sheet, which is currently being used by the company. Afterwards, the Xbar-R control chart is plotted. The sample of the SPC data record sheet currently being used by the company is shown in Fig. 4.

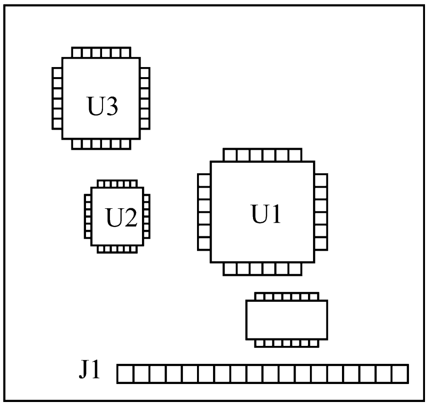

Fig. 3 Circuit design on a PCB

3.3 Analyse phase

Currently, six semi-automatic screening machines are used to manufacture the PSSD product. Therefore, the data on solder paste height of these six machines was collected from the company, and a process capability analysis was conducted for these screening machines in order to analyse the current printing performance. According to the analytical results, the process capability in machine no. 12 was not satisfactory because the capability index *Cp* was only 1.021, which was less than 1.33 (the four-sigma level). Moreover, another capability index *Cpk* was 0.387. This showed that the screening process was off-centre. As shown in the capability plot in Fig. 5, there was a high variance in the solder paste height and there was a mean shift in the height distribution.

3.4 Improve phase

In the analysis of the current printing performance, the result showed that the screening process capability of machine no. 12 was not satisfactory. After discussing the problem with the mechanical engineers in the company, it was determined that the designed experiments should be conducted on machine no. 12 in order to determine the optimal settings of all the CTQ input factors in the screening process. In this phase, DOE was used as a core statistical tool for the sigma level improvement.

In the initial experiments, several possible factors that might have influence on the printing performance were taken into account. These experiments were used to screen out new factors that have influence on the printing performance. These significant factors would then be included together with the already-known significant factors (solder paste viscosity, speed of squeegee, and pressure of squeegee) in further experiments. The aim of the further experiments was to determine the standard settings of all the significant factors. By using these optimal settings in the screening process, the printing performance could be improved. As a result, the sigma level can also be enhanced significantly. The details of the improve phase are given in Sect. 4.

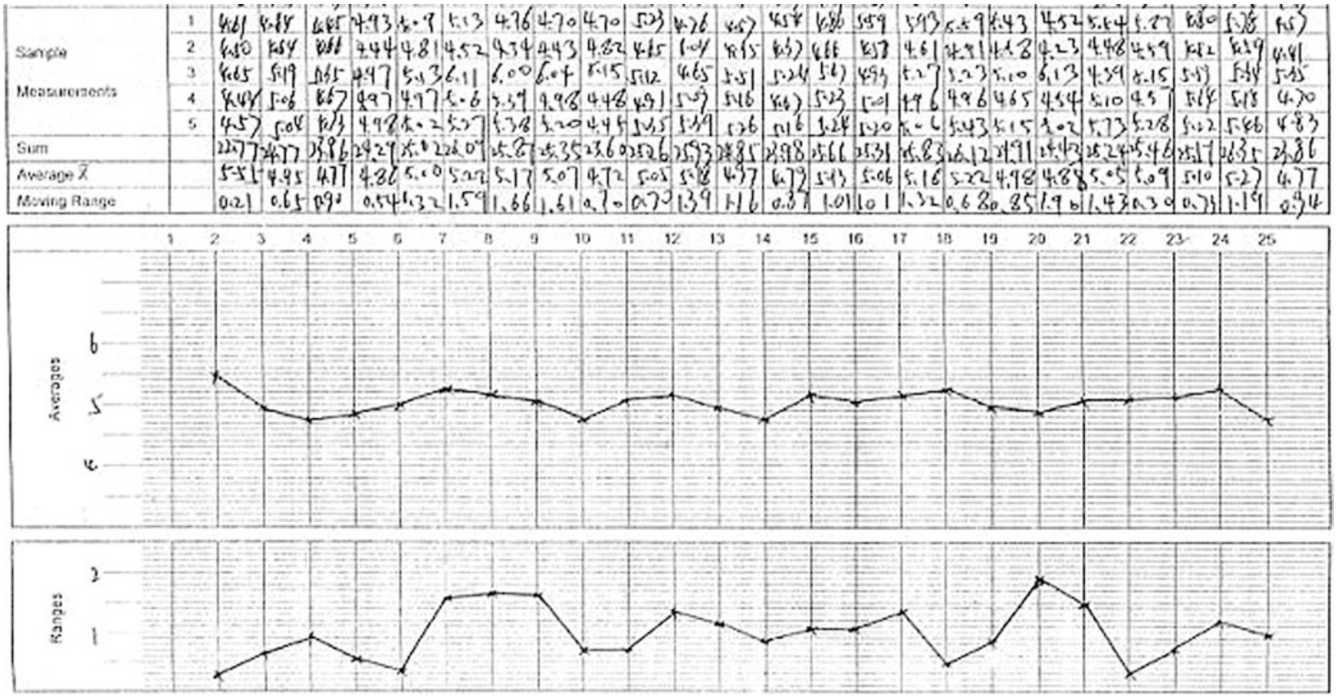

Fig. 4 SPC data record sheet

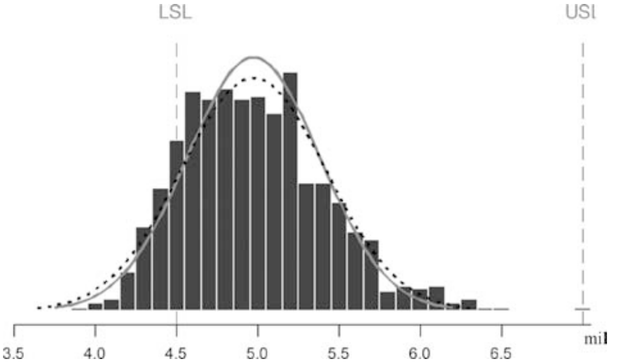

Fig. 5 Capability plot of machine no. 12

3.5 Control phase

To sustain the improvement of the sigma level in the screening process, some control strategies were recommended for the company. For example, the CTQ input factors should be monitored by control charts over time, so that the solder paste height variation and the sigma level can be controlled continuously. The descriptions of the recommended control strategies are provided in Sect. 5.

4 Improvement using DOE

DOE had been adopted in order to improve the sigma level. Initial experiments were to screen out the factors that might have influence on the printing performance and the further experiments were used to determine the optimal settings of the significant factors. The details of the initial and the further experiments are as follows:

4.1 Initial experiments

By referring to several research studies on SMT [1, 3, 4], many new factors that may affect the printing performance in the screening process were identified. However, it was impossible to consider all these factors in the initial experiments. Therefore, only four new factors were selected. They were the age of stencil, solder paste volume, blade type, and side of stencil. The descriptions of these factors are as follows:

Age of stencil duration of stencil use. The surface of a stencil becomes dented when aging. According to the mechanical engineers, the thickness of a stencil decreases as the duration of stencil use increases. Therefore, the age of stencil can probably affect the solder paste height during printing.

Solder paste volume refill volume of the solder paste in front of a squeegee. The hydraulic pressure increases as the refill volume in front of the squeegee increases. According to Hwang [5], the hydraulic pressure is directly related to the thickness of solder paste height, with higher hydraulic pressure resulting in a thicker solder paste.

Blade type the squeegee system has two types of blade: front and back blades. Currently, the front and back blades are used alternatively during printing. In fact, the front blade and back blade can function as two independent printing machines. This is because the machine settings can be adjusted for each blade individually. Therefore, the front and the back printings can produce different printing performance.

Side of stencil every stencil has two patterns on it, and hence two PCBs (one for left, one for right) are produced in each printing. It is easy to compare the solder paste height on the same point from the left and right patterns. If there is a significant effect of the side of the stencil on the solder paste height, the problem may be due to the squeegee system.

A full factorial experiment was carried out, and the whole experiment was completed in about one hour. There were 16 types of printing, and four PCBs were measured for each type of printing. In total, 64 PCBs were measured, and 320 solder paste height data were collected for analysis. The factors and their levels in the initial experiment are given in Table 1. The experimental conditions are as follows: (1) Room temperature: 25°C, (2) Room humidity: 56%, (3) Machine number: 12, (4) Number of operators: 1, (5) Model: Neptune, (6) Snap-off distance: nearly zero, (7) Squeegee pressure: 28 bar, (8) Squeegee speed: 0.7 inch/sec, (9) Point locations: J1, U1, U1, U2, U2, and (10) Specification: (4.5–7) mil.

From the experimental results, the main effect of the solder paste volume and the side of stencil showed significant influence on the solder paste height. The interaction between the blade type and the side of stencil was also significant. These significant effects were supported by the normal probability plot of the standardised effects shown in Fig. 6. As there was operator-to-operator variation in determining the solder paste volume, the refill volume of the solder paste for each printing might be different for different operators. Therefore, the solder paste volume was kept constant in further experiments. Since there were significant differences among front-left, front-right, back-left, and back-right printings, both blade type and side of stencil were considered in further experiments.

4.2 Further experiments

In further experiments, the refill volume of the solder paste in front of the squeegee was kept constant (small refill volume) since it was difficult to control the operator-to-operator variation in determining the solder paste volume. Apart from considering the new factors (blade type and side of stencil) in further experiments, the solder paste viscosity, speed of squeegee, and pressure of squeegee were also considered. The descriptions of these factors are as follows:

Solder paste viscosity ratio of shear stress to shear rate. According to Woodgate [1], viscosity is undoubtedly the most critical parameter of solder paste. He also pointed out that if the viscosity is too low, the solder paste will not remain in a rectangular shape when the stencil is lifted, but will flow out or “slump”, which can cause solder shorts. If, on the other hand, the viscosity is too high, the squeegee will not be able to completely fill the holes.

Speed of squeegee rate at which it travels in direct contact across the stencil. The force, speed, stiffness, angle and length of the squeegee are critical in solder paste printing. A slower speed does not improve paste deposit yield, while a faster speed causes the paste to skip some openings [3].

Pressure of squeegee force applied per unit area on the stencil by the squeegee. The force setting on the squeegee should be adjusted carefully so as to produce a clean stencil surface on a single pass. Greater force results in excess paste scooping. Less force leaves uneven paste deposits and smearing on the lands due to paste bleed under the stencil [3].

Side of stencil every stencil has two patterns on it, and two PCBs (one for left and one for right) are produced in each printing. In the initial experiments, the side of the stencil showed significant influence on the solder paste height.

Blade type the squeegee system has two types of blades: front and back blades. Normally, front and back printings are performed alternatively during printing. The front and back blades thus act as two independent printing machines. This is because the machine settings can be adjusted for each blade individually. Therefore, it is possible for the front and back blades to produce different printing performance. According to the initial experiments, the blade type had interaction with the side of the stencil on the effect of the solder paste height.

Table 1 The levels of each factor in the initial experiments

	Level 1	Level 2
Age of stencil	old (25 months)	new (8 months)
Solder paste volume	small	large
Blade type	front	back
Side of stencil	left	right

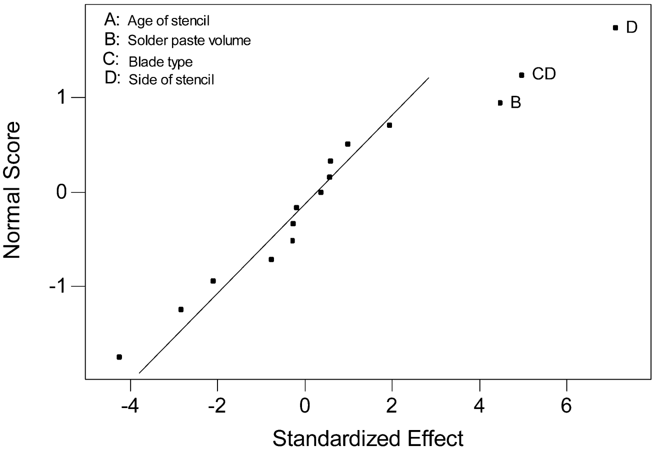

Fig. 6 Normal probability plot of the standardised effects

Table 2 The levels of each factor in the further experiments

	Level 1	Level 2	Level 3
Solder paste viscosity	< 150 mPa.s	> 190 mPa.s	/
Speed of squeegee	0.4 inch/sec	0.7 inch/sec	1 inch/sec
Pressure of squeegee	18 bar	28 bar	/
Side of stencil	Left	Right	/
Blade type	Front	Back	/

A full factorial experiment was carried out, and the whole experiment was completed in about two hours. There were 48 types of printing, and two PCBs were measured for each type of printing. In total, 96 PCBs were measured, and 480 solder paste height data were collected for analysis. The factors and their levels in the further experiments are given in Table 2. The experimental conditions are as follows: (1) Room temperature: 25°C, (2) Room humidity: 58%, (3) Machine number: 12, (4) Stencil number: 25 (new), (5) Number of operators: 1, (6) Model: Neptune, (7) Snap-off distance: nearly zero, (8) Point locations: J1, U1, U1, U2, U2, and (9) Specification: (4.5–7) mil.

4.3 DOE results

To study the influence of these factors on the solder paste height and to draw conclusions, the main effect plots and the interaction plots were used. A main effect is defined as the change in response produced by a change in the level of the factor, and an interaction between the factors occurs when the difference in response between the levels of one factor is not the same at all levels of the other factors [6, 7]. The responses for the plots were the average of five data points (height average) and the natural logarithm of the variance of five data points (height variation).

From the main effect plots shown in Fig. 7, the pressure of squeegee, blade type, and side of stencil were significant factors for the height average. From the main effect plots shown in Fig. 8, the solder paste viscosity, speed of squeegee, blade type, and side of stencil were significant factors for the height variation. From the interaction plots for the height average shown in Fig. 9, the interaction between solder paste viscosity and blade type showed significant influence on the solder paste printing performance. At high viscosity, the height difference between the front and back blades was relatively large, i.e. 0.36 mil. At low viscosity, however, the height difference between the front and back blades was relatively small, i.e. 0.05 mil. The interaction between the speed of squeegee and blade type was also significant. At high or medium squeegee speed, the height difference between the front and back blades was large, i.e. 0.36 mil for high squeegee speed and 0.22 mil for medium squeegee speed. At low squeegee speed, the front and back printings gave similar printing performance. The height difference was only 0.01 mil.

The higher order interactions were not considered for further analysis because the effects of these interactions were not significant. As the data on solder paste height was subjected to analysis of variance (ANOVA), the significant effects can also be confirmed by ANOVA. The ANOVA table is shown in Table 3.

From the analytical results, the solder paste viscosity, speed of squeegee, blade type, and side of stencil were significant factors for the height variation. Therefore, low solder paste viscosity (< 150 mPa.s), low speed of squeegee (0.4 inch/sec), front blade, and right side of stencil could result in small height variation. By using these optimal settings, the variation of the solder paste height can be reduced. After reducing the height variation, the sigma level of the screening process can be improved.

5 Recommended control strategy and predicted performance

After conducting the designed experiments, some control strategies for the critical-to-quality factors in the further experiments were recommended. The brief conclusions for each factor are as follows:

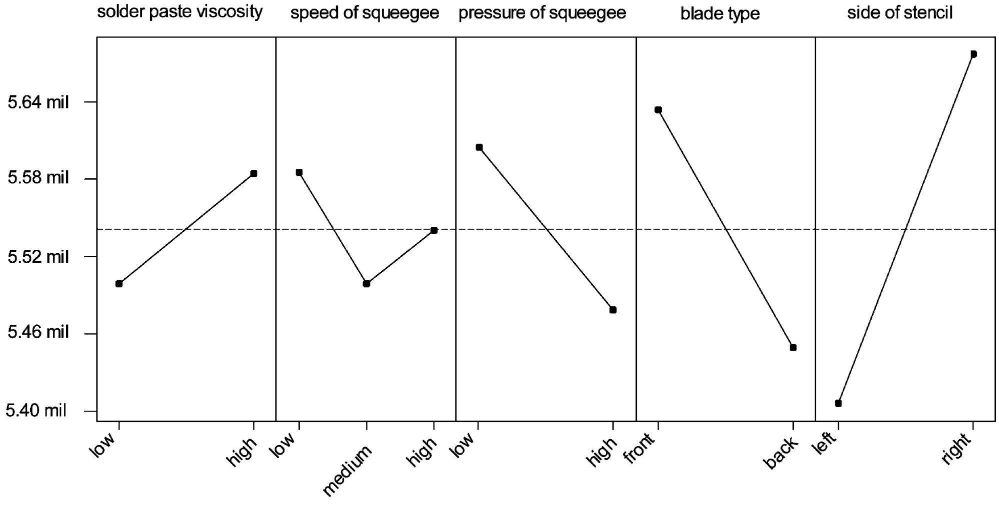

Fig. 7 Main effect plots for height average

Solder paste viscosity According to the experimental results, low solder paste viscosity (< 150 mPa.s) can reduce height variation within the board and hence can achieve better printing performance in the screening process. It is recommended solder paste viscosity be maintained at a low level (150 mPa.s) and that it be monitored it by the control chart over time.

Speed of squeegee The relatively low squeegee speed (0.4 inch/sec) is recommended as far as this low speed can optimise the printing performance of the screening process. The low printing speed can adversely affect the production yield. Therefore, the production yield should be kept above an acceptable level as the printing speed decreases.

Pressure of squeegee A low squeegee pressure (18 bar) should be set for a new stencil and the squeegee pressure should be increased progressively as the duration of using the stencil increases. By doing this, the squeegee pressure can compensate the deformation of stencil as the duration increases.

Side of stencil It is suggested that the company record the duration of using the squeegee so that the correlation between the side of the stencil and the age of the squeegee on the influence of the solder paste height can be studied.

Blade type As machine settings such as squeegee speed and squeegee pressure can be adjusted individually for the front blade and the back blade, the two blades can act as two independent printing machines. Therefore, it is recommended that the company study and optimise the front and back blades independently.

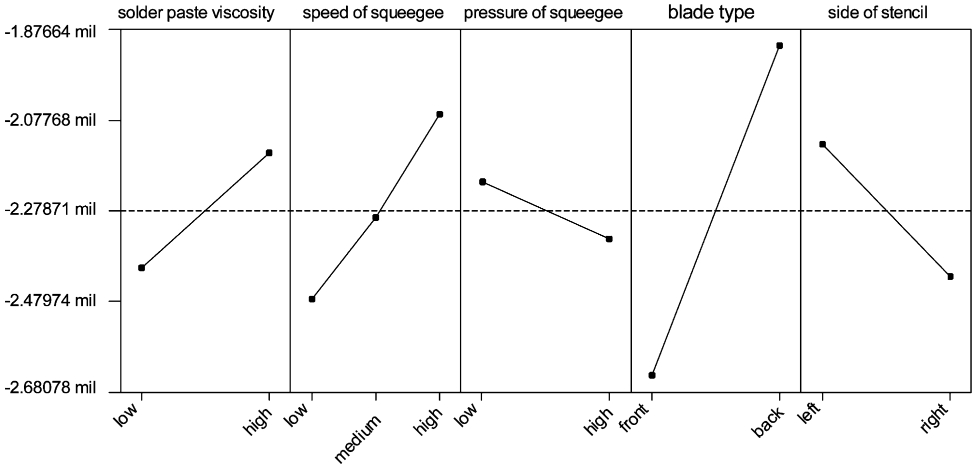

Fig. 8 Main effect plots for height variation

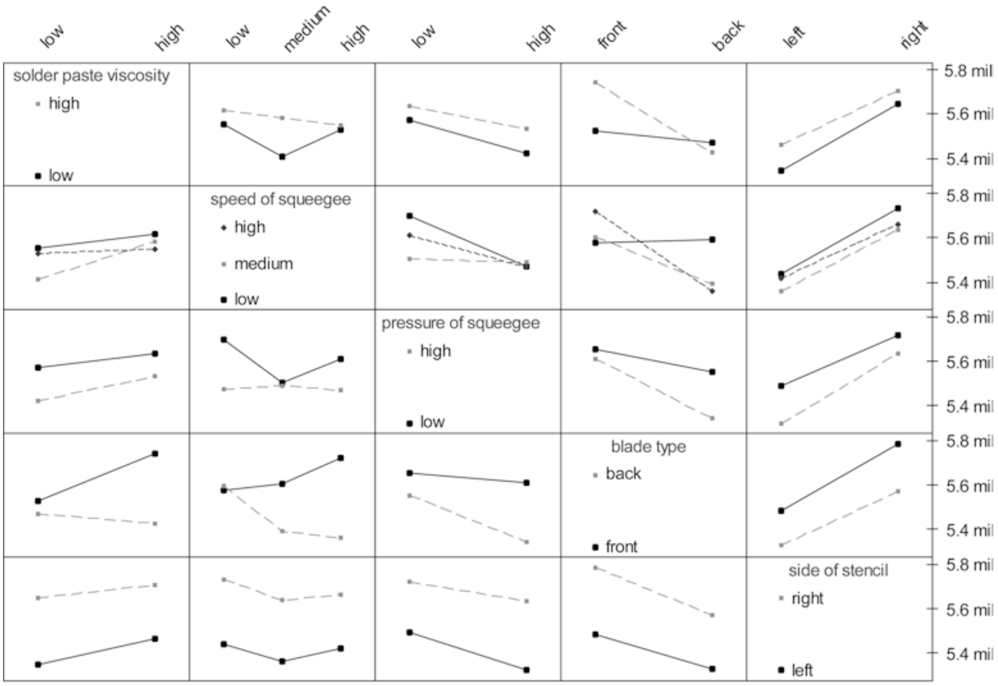

Fig. 9 Interaction plots for height average

Table 3 The ANOVA table for the height average in the further experiments

Source	DF	Seq *SS*	Adj *SS*	Adj *MS*	*F*	*P*
Viscosity	1	0.17802	0.17802	0.17802	3.15	0.082
Speed	2	0.12185	0.12185	0.06093	1.08	0.348
Pressure	1	0.38481	0.38481	0.38481	6.82	0.012
Type	1	0.82103	0.82103	0.82103	14.55	0.000
Side	1	1.76313	1.76313	1.76313	31.24	0.000
Viscosity*speed	2	0.09844	0.09844	0.04922	0.87	0.425
Viscosity*pressure	1	0.01407	0.01407	0.01407	0.25	0.620
Viscosity*type	1	0.40638	0.40638	0.40638	7.20	0.010
Viscosity*side	1	0.01854	0.01854	0.01854	0.33	0.569
Speed*pressure	2	0.17951	0.17951	0.08975	1.59	0.214
Speed*type	2	0.56765	0.56765	0.28383	5.03	0.010
Speed*side	2	0.01012	0.01012	0.00506	0.09	0.914
Pressure*type	1	0.16683	0.16683	0.16683	2.96	0.092
Pressure*side	1	0.04361	0.04361	0.04361	0.77	0.384
Type*side	1	0.02239	0.02239	0.02239	0.40	0.532

Table 4 Comparison of printing performance before & after using optimal settings

	Mean	S.D.	*Cp*	*Cpk*	Sigma level	ppm	COQ
Before	4.974	0.408	1.021	0.387	1.162	~122,173	> 40% of sales
After	5.750	0.211	1.975	1.975	5.924	~3.4	< 1% of sales

To conclude, the optimal settings are low solder paste viscosity (< 150 mPa.s), low speed of squeegee (0.4 inch/sec), right side of stencil, and front blade type. By using these optimal settings, the variation of the solder paste height can be reduced, and therefore the sigma level of the screening process on machine no. 12 can be improved.

The comparison of the printing performance before and after using the optimal settings is shown in Table 4. After using the optimal settings, the sigma level of the screening process can be improved from 1.162 to 5.924. This shows that a nearly six-sigma level performance can be achieved. According to Harry and Schroeder [2], the defect level in parts per million (ppm) would become 3.4 and the cost of quality (COQ) would be less than one percent of the sales. As a result, after using the optimal settings, the cost of quality for the company is significantly reduced.

6 Conclusion

In the improve phase of the DMAIC approach, DOE was used to identify the optimal settings of the critical-to-quality factors. By using the optimal settings, the sigma level of the screening process could be improved, and hence a nearly six-sigma performance can be achieved. Undoubtedly, DOE is the core statistical tools for six-sigma improvement. It is recommended that successful implementation of the DMAIC approach in the screening process should be translated to similar manufacturing processes in the PCB industry, so that the impact of the DMAIC approach can be maximised.

In the screening process, many factors can affect the solder paste printing performance; however, due to time and financial constraints, only five factors were included in the designed experiments: solder paste viscosity, speed of squeegee, pressure of squeegee, side of stencil, and blade type. According to Marcoux [3], the force, speed, stiffness, angle, and length of the squeegee are critical in the solder paste printing. It is therefore recommended that the company consider these factors in the designed experiments as well in order to identify the effect of these factors on the printing performance. It is also suggested that the company extend the designed experiments to different machine and stencil combinations, so that the optimal settings can be applied to all machine and stencil combinations. For recent advances in statistical quality techniques, the readers are recommended to refer to Tsung and Shi [8], Tsung et al. [9], Tsung [10], and Tsung and Apley [11].

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