Defective Reduction from Solder-Paste Strains on a Flexible Printed Circuit

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***Abstract*—During the last decades, consumer electronic devices have been integrated with our everyday activities. One component that helps these devices to achieve with their small sizes and versatile functions is a flexible printed circuit (FPC). Each FPC consists of various electronic components on a flexible conducted surface using a special assembling process, called surface mount technology (SMT). Within the SMT process, the most significant defective is the solder-paste strain on pads of a FPC, which accounts for 0.13% of total products manufactured. Such defective products cannot be reworked. Small group techniques revealed that the cleaning routine of a solder printing machine is one of the root causes. Followed the six-sigma approach, the defective rate is selected as the main response for hypothesis tests and design of experiment. Determining of the optimal parameters in the cleaning routine using two-level full factorial design with two replications suggest same direction and 80 cm per second cleaning speed without vacuum as optimal setting. The result after one month of implementation showed that the defective rate was reduced to 0.06%.**

***Index Terms*—flexible printed circuit, xix sigma, screening in SMT process, design of experiments.**

I. INTRODUCTION

During the last decades, consumer electronic devices, such as mobile phones and cameras, have been integrated with our daily activities. One component that helps these devices to achieve their small sizes and versatile functions is a flexible printed circuit (FPC) as shown in Fig. 1.

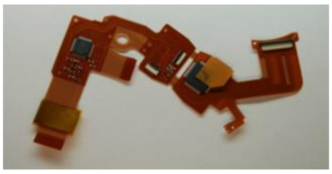

Figure 1. An example of flexible printed circuit

Because of its flexible copper sheet and tightly packed components, a FPC is thinner than a traditional printed circuit board (PCB) as well as more popular in small consumer electronic devices. Each FPC consists of various electronic components on a flexible conducted surface or plastic substrates using a special assembling process, called surface mount technology (SMT), that places electrical components directly on the flexible surface without any hole. The technology is vital to electronic products as it provides high production yield and accuracy as well as low operation costs. In general, SMT consists of three sub-processes.

- **Screening:** Solder pastes are screened on the stencil of a specific model and passed through apertures by a squeegee
- **Mounting:** Electronic components are positioned onto designed locations on a screened FPC.
- **Reflowing:** A screened FPC is transported and heated so that components are attached.

Among these three sub-processes, the screening sub-process has been recognized as the most critical one as it accounts for more than half of defective products by Tsai [1]. Furthermore, many researchers have discovered the strong relationship between solder pastes in both a PCB and a FPC and the performance of electronic devices. For example, Li *et al*. [2] found that the deviated solder thickness from nominal parameter could affect the performance of a PCB. The result was confirmed and further analyzed by Wohlrabe [3] who revealed the volume and the printed area are important factors to the quality. As a practical way to improve the defective rate, he also experimented on different screening setting, such as cleaning cycle, squeegee direction, and waiting time. In both articles, the authors utilized the six-sigma approach as a tool to improve the screening sub-process.

In this article, we analyzed the SMT historical data of a FPC factory in Thailand and found that the most significant defective is the solder-paste strain on pads of a FPC. It is serious defective as solder-paste strains may cause short circuit once a device is connected with an electrical source or may cause transmitting errors as a device usually has multiple pads for difference functions. Such the defective products cannot be reworked causing wastes in terms of raw materials and production time. Before reported our analysis and discussed our solution, it is useful to highlight the six-sigma approach.

II. SIX-SIGMA APPROACH

As the most popular tool for process improvement, the six-sigma approach was pioneered by Motorola. The approach relies on the statistical analysis and quality control methods and consists of five phases: define-measure-analysis-improve-control (DMAIC) [4]. Each

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phase is designed to achieve a certain goal and coupled with a set of standard quality control tools. The goal of the define phase is to select root causes of a main defect using Pareto Diagram, Cause and Effect Diagram, and Failure Mode and Effect Analysis (FMEA). For example, Pongtrairay and Senjuntichai [5] defined spiral defects in hard disk drive manufacturer using Pareto Diagram and proposed a list of possible factors using FMEA. Having identified the main defect, they proceeded into the measure phase by selecting and testing measurement system to ensure repeatability and reproducibility. In the analyze phase, possible factors are probed using hypothesis testing to narrow statically significant factors before applying design of experiment (DOE) to capture interactions among main factors and to select optimal parameters for the next phase. The goals of the improve phase is to implement such parameters in the practical environment. Once the implementation is completed, the control phase is set up to maintain the sustainability of the result and the continuity of improved processes using control chart and statistical process control. Having reviewed the methodology, the remaining sections are organized by the phases in DMAIC.

III. Define Phase

During Jan - Jun 2014, the FPC factory observed the surge of defects in SMT. The primary data analysis showed that 0.22% FPC of a certain model can be grouped into seven defective as shown in Fig. 2.

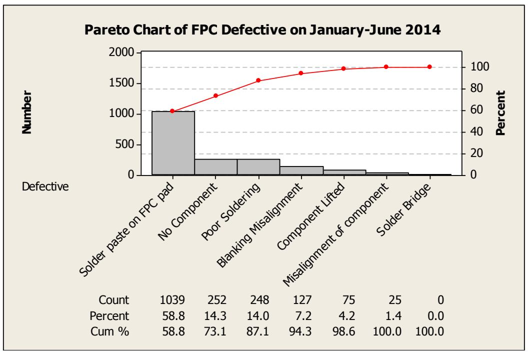

Figure 2. Pareto diagram of FPC defective during Jan-Jun 2014

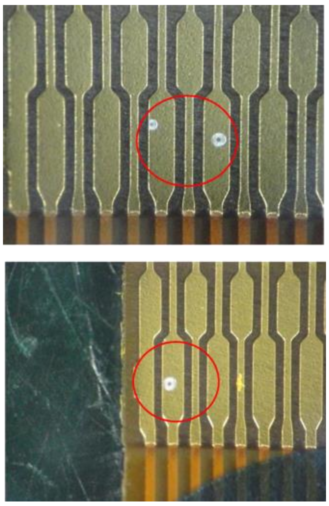

Figure 3. Solder-paste strains are spotted on FPC pads

The Pareto Diagram reveals that the majority of defective rate that accounts for 58.8% of defect products or equivalent to 0.13% of total products manufactured is the solder-paste strain on pads of a FPC as shown in Fig. 3.

Such the defective cannot be reworked and may cause short circuit when a FPC pad is assembled onto connectors or other components.

IV. Measure Phase

To determine the root causes, all engineers and technicians were gathered to brainstorm possible causes of the solder-paste strain defective using Cause and Effect Diagram. The result and further FMEA analysis led to three causes that account for 80% of scores.

- **Human Error**: An operator may ignore instruction, especially manual cleaning.
- **Machine Error:** A screening machine may not follow automatic cleaning routine or poorly execute routine, e.g. using only a front cleaning roller to wipe a stencil.
- **Cleaning Routine**: Parameters in cleaning routine may be improperly selected.

The meeting concluded that the cleaning routine is the most interesting cause as the other two causes can be prevented with training and maintenance. In addition, engineer found the remaining paste on a stencil surface that leads to further speculation of cleaning routine in screening machines as shown Fig. 4.

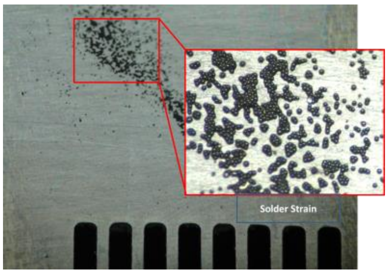

Figure 4. Solder-paste strains remain on a stencil surface

Therefore, the team decided to focused on a single FPC model in a certain digital camera and used it as pioneer for other models. Before discussing possible factors that may affect the routine in the analyze phase, it is nesscary to understand the automatic cleaning routine as shown in Fig. 5.

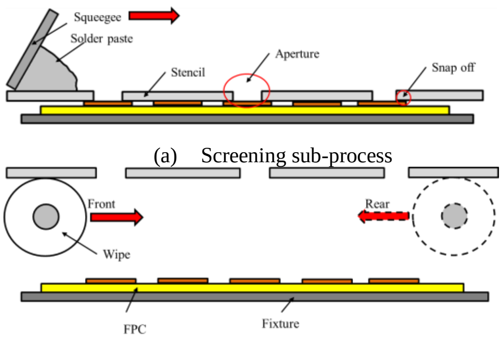

Figure 5. Screening and cleaning FPC

Fig. 5(a) shows the screening sub-process that occurs before the automatic cleaning routine. It is nesscary to note that the stencil literally touch a FPC during the sub-process or zero snap off distance. The cleaning routine begins after the machine drops a fixture and a screened FPC to create a cleaning chamber for the routine. First, the stencil is saryed with chemical designed to disolve solder pastes. Then, the loosen solder pastes are wipped by single roller attached with wiping paper that move from both front-end and rear-end of the machine. The machine is also equiped with vacumn to remove any solder pastes inside the apertures.

V. Analyze Phase

In the follow-up meetings, the team selected the defective rate as the main response and discussed potential factors that are available and manageable in the cleaning routine, particularly

- **Direction** controls the direction of cleaning roller. An operator can choose same single direction or different front-and-rear direction
- **Speed** decides the velocity of cleaning roller. It can be selected ranging from 50 cm/s to 80 cm/s.
- **Vacuum** is an optional routine creating negative pressure in a cleaning chamber. Because of its connection to the central system, an operator chooses whether turn the vacuum on or not.
- **Extra clean** is also an optional routine that allows additional wiping by cleaning roller.
- **Cycle** is the frequency in which a stencil is cleaned by the machine. It can be ranged from exercising the cleaning routine every screening or never exercising the cleaning routine. Currently, it is set at one for every ten screening.

Before probing these factors and selecting significant ones using hypothesis test, it is important to choose the sample size. Based the main response, the minimal sample size for the two-sided test of a binomial proportion was suggested by Montgomery [6] as shown in Expression 1.

$$n = \frac{[z_{\alpha/2}\sqrt{p_1(1-p_1)} + z_\beta\sqrt{p_2(1-p_2)}]^2}{(p_1 - p_2)^2} \qquad (1)$$

TABLE I. Hypotheses Test of Possible Factors

Factor	Sample size	p-value	Power of test	Conclusion
A) Direction	37,100	0.000	97.51%	Significant
B) Speed	37,100	0.004	81.94%	Significant
C) Vacuum	37,100	0.000	98.41%	Significant
D) Extra clean	37,100	0.696	90.29%	No Significant
E) Cycle	37,100	0.369	85.33%	No Significant

The expression shows that sample size n depends on the current and expected defective rates p_1 and p_2 as well as standard normal distribution of type I (significant level) $z_{\alpha/2}$ and type II error z_β (power of test). The expression suggests the sample size of 37,100 FPCs. This requires approximately nine operational shifts to complete each factor. The hypothesis testing leads to the selection of factors for DOE as shown in Table I.

The result shows that factors A, B, and C are significant factors at 5% significant level with the power of test greater than 80%.

Because of few factors, the full factorial design is proposed. Nevertheless, the initial trials on a single replication suggest that multiple-replication experiments should be used because the residual of the result fails the normality test. As a result, the 2^{3} DOE or 16 runs with sample size of 6,300 FPCs for each run is selected at 5% significant level and power of test greater than 90% [7].

Since the main response is classified as the proportion, we followed the suggestion by Bisgaard and Fuller [8] to prevent the violation of constant variance assumption by using Freeman and Turkey's transformation as shown in Expression 2.

$$\text{F\& T} = \frac{1}{2}\left(\arcsin\sqrt{\frac{n\hat{p}}{n+1}} + \arcsin\sqrt{\frac{n\hat{p}+1}{n+1}}\right) \qquad (1)$$

This transformation is a function of sample size n and defective rate $\hat{p}$ that transforms defective rate into F&T value. To ensure the validity and reliability, the residual plots of the experiment are depicted in Fig. 6.

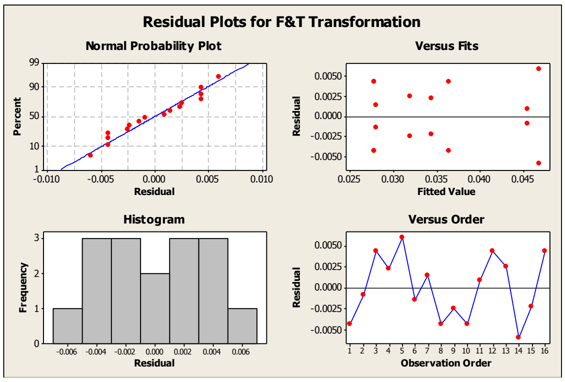

Figure 6. Residual plots for F&T Transformation

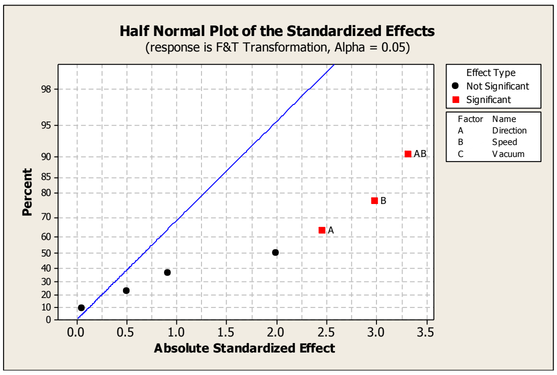

Figure 7. Normal plots of the standardized effects

In Fig. 6, the residuals of the normal probability plot are aligned along the normal line with the p-value greater than 0.05. In addition, the plot between the residuals and their fitted values exhibits no pattern. These findings indicate that the residuals are independent and normally distributed with a stable variance. Next, the interaction effects are analyzed using a half normal plot as shown in Fig. 7.

The plot shows that two main effects or factors A and B and their interaction significantly affect the solder-paste strain on FPC pads.

VI. Improve Phase

This phase uses the results of DOE and the findings in the analyze phase to select an optimal parameter using ANOVA analysis as in shown Table II.

TABLE II. ANOVA of Fit F&T Transformation

Factors	Effect (10^{-3})	Coef (10^{-3})	p-value
Constant		36.9	0.000
Direction	6.38	3.19	0.034
Speed	-7.81	-3.91	0.014
Vacuum	-1.07	-0.53	0.680
Direction × Speed	-8.90	-4.45	0.007
Direction × Vacuum	2.00	0.01	0.994
Speed × Vacuum	-5.59	-2.80	0.055
Direction × Speed × Vacuum	2.19	1.09	0.406

note: with SE coefficient 0.001247

The ANOVA confirms the half normal plot that the direction and speed factors and their interactions are statistically significant to the solder-paste strain on pads of a FPC at the confident level of 95% or equivalent to the standard error of coefficient of 1.247×10^{-3}. To determine optimal parameters, the F&T transformation of three factors are plotted and analyzed as shown in Fig. 8 and 9.

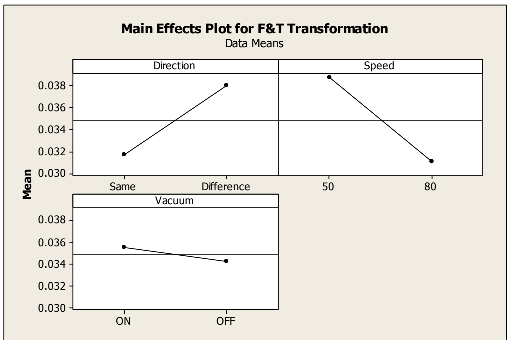

Figure 8. Normal plots of the standardized effects

In Fig. 8, the same one-way cleaning direction and the cleaning speed of 80 cm per second reduce the defective rate. However, the operating vacuum increases the defective rate. This counter-intuitive finding can be explained by the appearance of small hidden solder pastes inside apertures. Without any wiping to remove, these solder pastes are moved onto a stencil surface thereby creating solder-paste stains.

In Fig. 9, the interaction between of direction and speed factors is interesting as it reveals that the same wiping direction can reduce the defective rate regardless of the speed of cleaning roller. The explanation of this interaction is that the same single direction wiping causes solder pastes to only one side of a stencil thereby more effective to remove solder pastes. One drawback of the same direction is a longer cleaning cycle time as the cleaning roller has to reposition itself every time after wiping. Therefore, an operator should select high cleaning speed to reduce the cleaning cycle time and to increase the productivity. After selecting the parameter of the cleaning routine—same direction and 80 cm per second cleaning speed without vacuum, the remaining phase of DMAIC is the control phase.

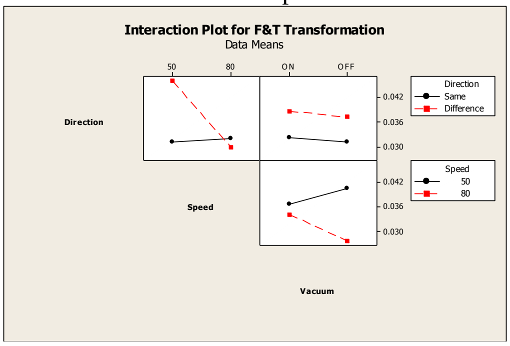

Figure 9. Normal plots of the standardized effects

VII. Control Phase

Under the optimal parameters, the team continuously monitored the production yield and the defective rate of the selected camera model for 30 days with the daily average of 4,550 FPCs and represented the daily defective rate as shown in Fig. 10.

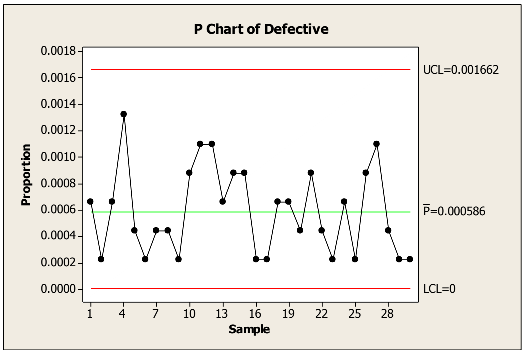

Figure 10. P Chart of solder-paste strains on FPC pad defect after improvement

The p-chart in Fig. 10 shows the average defective rate is 0.06%. To ensure success, the check sheet for of solder-paste strain on pads of a FPC is designed and incorporated into the work instruction. Moreover, periodic trainings are proposed to address the parameters of the cleaning routine and to enhance awareness of human error issue.

VIII. Conclusion and Limitation

In this article, we reported the implementation of DMAIC phases in a Thai electronic factory that faced high defected FPCs. The SMT historical data shows that the solder-paste strain is an urgent defective and requires immediate attention as this defective cannot be reworked and affects performance of finished products. Focused on a single FPC model in camera, small group techniques and statistical tools narrow down potential factors into three significant ones: direction, speed, and vacuum. Then, two-level full factorial with two replications design of experiment is used to determine optimal setting. The experimental result concludes that the optimal parameters are same direction cleaning, 80 cm per sec cleaning speed without vacuum. With the new cleaning parameters, and the defective rate was reduced from 0.13% to 0.06%. To safeguard the improvement, we implemented p-chart to control the variation of defective rate.

The key limitations of this approach are number of samples required and model specification. Because the defective rate is derived from attribute data, it requires large numbers of samples. Furthermore, the optimal parameters in the cleaning routine may depend on the SMT machine. Nevertheless, the results in the article can be served as primary setting for other models.

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