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Screen Printing Process Design of Experiments for Fine Line Printing of Thick Film Ceramic Substrates

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Abstract

Screen printing has been the dominant method of thick film deposition because of its low cost. Many experiments in industry have been done and many models of the printing process have been developed since the 1960's. With a growing need for denser packaging and a drive for higher pin count, screen printing has been refined to yield high resolution prints. However, fine line printing is still considered by industry to be difficult. In order to yield high resolution prints with high first pass yields and manufacturing throughput, the printing process must be controlled stringently.

This paper focuses on investigating the effect of manufacturing process parameters on fine line printing through the use of statistical design of experiments (DOE). The process parameters include print speed, squeegee hardness, squeegee pressure, and snap-off distance. Response variables are mean width and standard deviation of 10 mil, 8 mil, and 5 mil lines in both parallel and perpendicular directions relative to the squeegee travel direction. It is concluded that the squeegee hardness has a statistically significant effect on both directions, while the squeegee speed has an effect only on the parallel direction. The implementation procedures of the experimental design are presented. The analysis of a 2^k factorial design with center points pertaining to the fine line printing experiment is discussed in detail.

Key Words: Screen Printing, Design of Experiments, Fine Line, Thick Film, Fine Pitch

1. Introduction

Surface Mount Technology (SMT) is the trend in electronic packaging and interconnection because it allows manufacturing lighter weight, smaller size, and higher performance products. SMT can be defined as the placement and attachment of surface mount components directly onto a pad on the substrate via a solder joint. In contrast, conventional technology is that the component's lead is connected to the substrate via a through-hole insertion and a solder joint. SMT first occurred in military and aerospace electronic products during the mid-1960s in order to achieve the highest electronic densities and performances. Today it is used in almost all types of electronic products from satellites to automobiles, computers to home appliances.

With a growing need for denser packaging and a drive for higher pin count, SMT has evolved from standard SMT to fine pitch SMT and ultra fine pitch SMT. There are two definitions of fine pitch. One is defined by the Institute for Interconnecting and Packaging Electronic Circuits (IPC) as leads from 100 μm to 500 μm (4 - 20 mils) (SMC-TR-001). The other is proposed by a printed circuit board consortium calling itself the "October Group" as a pitch of 500 - 1000 μm (20 - 40 mils), and ultra fine pitch for pitches of less than 500 μm (20 mils) [1]. The latter definition of fine pitch and ultra fine pitch has been popularly used.

Screen printing technology began to be widely used to paste conductors, resistors, and dielectrics during the mid-1960s. Nowadays screen printing has become the dominant method of thick film deposition. The advantages of screen printing are low cost, quick turn around, reduced paste volume, and good gasketing (no smear). However, smaller powder (in the range of a few microns to submicrons) or low viscosity paste is required during screen printing. In addition, thick prints are difficult. These limitations make it difficult to print solder paste using screens with smaller pitch

and higher lead count requirements. The main reasons are that solder pastes contain larger particles (in the range of approximately 75 μm to a few microns) and are generally higher in viscosity than thick film inks.

2. Review of Screen Printing Process

A schematic of the screen printing process is shown in Figure 1. The screen is supported by the emulsion in the openings. The squeegee pushes down on the screen, causing the screen to come into contact with the substrate. When the squeegee is moved along the screen surface, it pushes the paste through the openings, which covers the desired areas of the substrate. Screens count on a snap-off distance and the tension of the screen to cause the screen to peel out of the ink after the squeegee has gone by.

There are many variables that affect the printing process. The components of the screen printing process include the printer, the substrate, the screen, the squeegee, the thick film paste, and the process parameters. The detailed variables that influence the printing process are summarized in Figure 2.

Many experiments in industry have been done and many models of the printing process have been developed since the mid-1960s. Miller [2] studied the relationships between the amount of paste deposited and the screening process such as the mesh size, paste rheology, line width, etc. Austin [3] described the effects on printing thickness of squeegee attack angle, squeegee blade characteristic, and substrate variations. Bacher [4] investigated the effect of screens on high resolution prints. Riemer [5, 6] presented a theory of the paste deposition process by screen printing. In his theory, the ink roll in front of the squeegee is treated as a pump generating high hydrostatic pressure close to the squeegee edge to inject ink into the screen meshes. Owczarek and Howland [7, 8] described a physical model of the screen printing process. They found that the angles of squeegees during printing decrease from the unformed angle of 45 degrees by about 20 degrees for hard squeegees (90 shore A) and by 30 – 40 degrees for soft squeegees (60 shore A).

Fine line printing with various types of thick film inks becomes a leading technology due to demand for smaller, lighter, and higher density products. In a recent analysis, boards with 125 μm (5 mils) lines/spaces are the most cost-effective for TQFPs and PBGAs, while boards with 100 μm (4 mils) lines/spaces are the most cost-effective for 1.0 mm and 0.8 mm pitch CSPs.[9] However, fine line printing, for example 100 μm (4 mils) lines/spaces, is still considered by industry to be difficult for mass production. More research and experiments need to be done to improve screen printed fine line resolution.

The quality of fine line printing is affected by a considerable number of variables, such as wire bias of the screen, the quality of the screen emulsion, viscosity and rheology of inks, and printing process parameters. This paper focuses on investigating the effect of manufacturing process parameters on fine line printing through the use of statistical design of experiments (DOE).

3. Design of Experiments

The goal of this experiment was to investigate the effect of the manufacturing process parameters on fine line printing. After the printing process was carefully reviewed, four factors were considered to be important variables on fine line printing quality and were chosen in this study. They were print speed, squeegee hardness, squeegee pressure, and snap-off distance. The response variables were defined as mean width and standard deviation of 0.25mm (10mil), 0.2mm (8mil), and 0.125mm (5mil) lines in both parallel and perpendicular directions relative to the squeegee travel direction. Figure 3 shows the inputs and outputs of this experiment.

The test pattern is shown in Figure 4. The pattern contained a group of different line widths: nominal 0.125mm (5mil), 0.2mm (8mil), and 0.25mm (10mil) line widths in both parallel and perpendicular directions. A microscope was used to measure the width of each line. 10 points on each line are measured. All 6 lines per print were measured yielding 60 width measurements and a total of 2,040 points in this experiment. Data were imported into a spreadsheet. The mean line width and the standard deviation of each line were then calculated.

In order to limit the number of experimental runs, a 2^4 factorial design with center points was selected. The center point refers to setting all factors at the middle level. Replication is essential to estimate the interaction between the factors. So a total of $2*(2^4+1)= 34$ runs were done. The 2^4 factorial design with center points provides an estimate of error, check for interactions, and check for quadratic effects. Table 1 summarizes the factors and levels for the experiment. Table 2 illustrates the DOE matrix. The next step was to randomize the order of the treatments. It should be noted that the randomization of the order of treatments is the cornerstone underlying the use of statistical methods in experimental design. The assumption that the observations are independently distributed random variables is usually valid by properly randomizing the experiments.

The substrates used in this experiment were 50x50 mm (2 x 2 inches) 96% alumina. The paste was Ag/Pd conductor paste. The polyurethane squeegee was set at 45 degree. The screen was 325 mesh, 28μm (1.1mil) wire diameter, 7.6μm (0.3 mil) emulsion. After printing, the substrates were dried and fired.

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Table 1. Factors and Levels

Parameter	High	Middle	Low
Squeegee hardness (shore type A)	90	80	70
Snap-off distance (mils)	50	40	30
Squeegee Pressure	High	Middle	Low
Squeegee speed (inch/sec.)	7	6	5

Table 2. 2^4 factorial with a center point design matrix

Run No.	Squeegee pressure	Squeegee hardness	Snap-off distance	Squeegee speed
1	L	L	L	L
2	H	L	L	L
3	L	H	L	L
4	H	H	L	L
5	L	L	H	L
6	H	L	H	L
7	L	H	H	L
8	H	H	H	L
9	L	L	L	H
10	H	L	L	H
11	L	H	L	H
12	H	H	L	H
13	L	L	H	H
14	H	L	H	H
15	L	H	H	H
16	H	H	H	H
17	M	M	M	M

4. Analysis of the data

The data results were analyzed using STATGRAPHICS@ to produce an Analysis of Variance (ANOVA), regression model, and assumption checking. It should be noted that the usual ANOVA in a 2^k design does not need center points. The center points are only used for regression model.

4.1 ANOVA

Before analysis of variance, the adequacy of the model should be investigated. The adequacy of the model consists of the normality assumption, uniform variance, and independence of errors. The check of the normality assumption usually uses the normal probability plot. Figure 5 illustrates the normal probability plot for the mean width of 0.2mm (8mil) parallel lines. There is nothing unusual. The plot of residual versus predicted in Figure 6 and the plot of residual versus experiment sequence in Figure 7 indicate that the uniform variance and independence assumptions are valid.

The analysis of variance for the mean width of 0.2mm (8mil) parallel lines is shown in Table 3. The P-values test the statistical significance of each of the factors. Since the P-values of squeegee hardness and squeegee speed are less than 0.05, these factors have a statistically significant effect on mean width of 0.2mm (8mil) parallel lines at the 95.0% confidence level. Table 4 summaries the significant main effects for all response variables. Mean 10 par means the mean width of 0.25mm (10mil) parallel lines, and Dev. 10 per means the standard deviation of 0.25mm (10mil) perpendicular line widths.

Table 3. ANOVA for mean width of 8 mil parallel lines.

Source	Sum of Squares	Df	Mean square	F-ratio*	P value
Main effects					
A:SnapoffDis	0.01162	1	0.01162	0.00	0.9635

B:Sque. Hard	160.967	1	160.967	29.61	0.0000
C:Sque. Pres	10.4082	1	10.4082	1.91	0.1810
D:Sque. Sped	39.4494	1	39.4494	7.26	0.0136
Interactions					
AB	5.85675	1	5.85675	1.08	0.3111
AC	11.1038	1	11.1038	2.04	0.1677
AD	2.4145	1	2.4145	0.44	0.5124
BC	4.41788	1	4.41788	0.81	0.3776
BD	6.74363	1	6.74363	1.24	0.2780
CD	0.37195	1	0.37195	0.07	0.7962
RESIDUAL	114.169	21	5.43664		
Total (corrected)	355.914	31			

* All F-ratios are based on the residual mean square error.

Table 4. Summary of significant effects for all response variables.

	Snap-off Distance	Squeegee Hardness	Squeegee Pressure	Squeegee Speed
Mean 10 Par		Yes		Yes
Mean 10 Per		Yes		
Mean 8 Par		Yes		Yes
Mean 8 Per		Yes		
Mean 5 Par		Yes		Yes
Mean 5 Per	Yes	Yes	Yes	Yes
Dev. 10 par				Yes
Dev. 10 per				
Dev. 8 par			Yes	Yes
Dev. 8 per				Yes
Dev. 5 par		Yes		
Dev. 5 per		Yes		

4.2 Regression model

From Table 4, we know that squeegee hardness and squeegee speed have statistically significant effects on fine line printing, while snap-off distance and squeegee pressure may not have significant effects at the designed level which described in Table 1.

A potential concern in the use of a 2^k fractional design is the assumption of linearity in the factor effects. Next a check was performed to determine whether a quadratic effect existed between squeegee hardness and squeegee speed. Note that all experimental data including center points are used for this. The regression model is:

$y = \beta_0 + \beta_1 SH + \beta_2 SS + \beta_3 SHSS + \beta_4(SS^2 + SH^2) + \varepsilon$

where

y is measured experimental value of a response variable;

$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ are coefficients;

SH is level of squeegee hardness (High = 1, middle = 0, low = -1)

SS is level of squeegee speed (High = 1, middle = 0, low = -1).

Note that SS^2 and SH^2 are confound here because the 2^2 design plus center points only has five independent runs so that we can only estimate 5 coefficients. The regression analysis indicates that there are no quadratic effects of squeegee hardness and squeegee speed. The scatter plot of the mean width of 0.2mm (8mil) parallel lines versus the squeegee hardness and the squeegee speed is shown in Figure 8. It indicates that the harder the squeegee and the lower the squeegee speed, the better the printed results.

5. Conclusions

A hard squeegee should be utilized in fine line printing. The squeegee hardness is the most important variable that influences the printing results obtained.

The snap-off distance and squeegee pressure at the experimental levels does not have significant effects on fine line printing, but they may relate to the selection of the screen tension.

The squeegee speed has a significant effect on lines that are parallel to the squeegee traveling direction. At the

experimental levels, the lower the speed, the better the printed results. However, the squeegee speed does not have a significant effect on perpendicular line width.

The finer the printed line, the greater the deviation. This means the process operating window becomes narrow in fine line printing and more strict process control is needed.

These experiments only focus on the printing process, more follow up experiments with additional emphasis on screen mesh, emulsion, paste, substrate, and cleaning techniques need to be performed.

6. Acknowledgment

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7. Biography

Jianbiao Pan is currently a Ph.D. candidate in the Department of Industrial & Manufacturing Systems Engineering at Lehigh University. His research interest is in manufacturing process and system, CAD/CAM, and process Control. He has worked for three years and held a project director position at Beijing Institute of Radio Measurement. He is a member of IMAPS, IEEE, and SME, and current chair of SME Lehigh University Student Chapter.

Dr. Gregory L. Tonkay is Associate Professor in the Department of Industrial and Manufacturing Systems Engineering at Lehigh University. He is the Director of the Electronics Manufacturing Laboratory and Associate Director of the George E. Kane Manufacturing Technology Laboratory. He has authored or coauthored over 25 technical papers. His areas of interest are manufacturing, automation, electronics manufacturing, and engineering education.

Alejandro Quintero is a senior majoring in Industrial Engineering with a minor in Portuguese at Lehigh University. He was a recipient of the 1997 General Electric Company Undergraduate Research and Fellowship Awards.

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Figure 1. Schematic diagram of the screen printing process

Figure 2. Factors that influence the screen printing quality

Figure 3. Inputs and outputs of this experiment

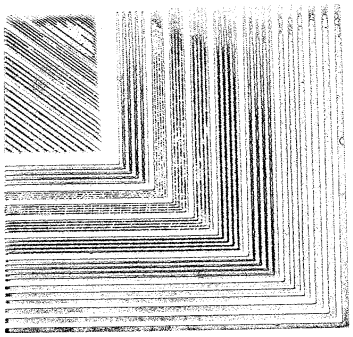

Figure 4. The test pattern

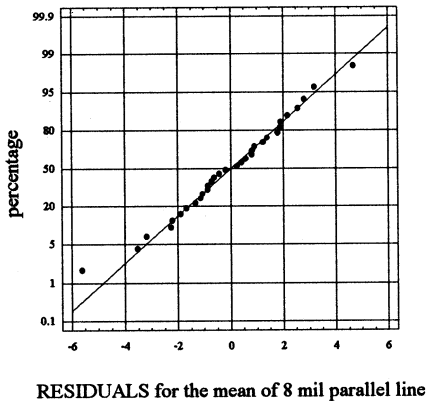

Figure 5. Normal probability plot for residuals of mean of 0.2mm (8 mil) lines

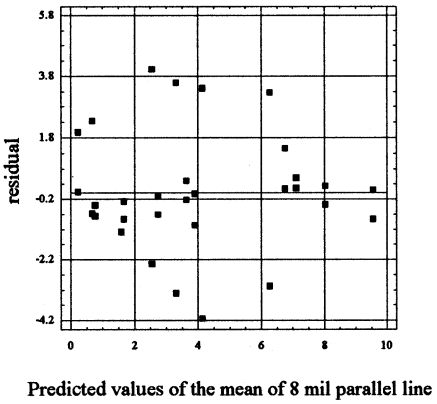

Figure 6. Plot of residuals versus predicted values

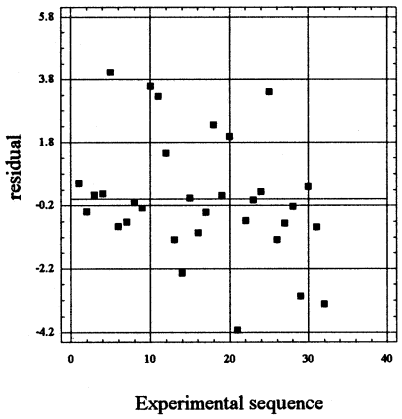

Figure 7. Plot of residuals versus experimental sequence

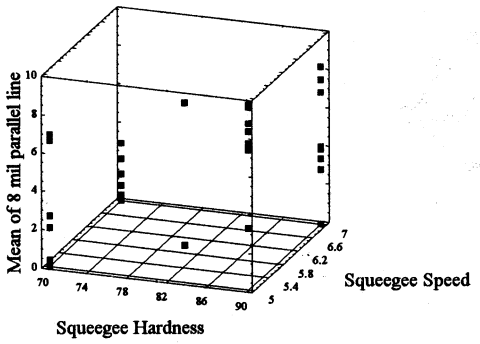

Figure 8. Plot of mean of 0.2mm (8 mil) parallel lines versus squeegee hardness and squeegee speed