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PCB Design Optimization of 0201 Packages for Assembly Processes

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ABSTRACT
The demand for 0201 components in consumer products will increase sharply over the next few years due to the need for miniaturization. It is predicted that over 20 billion 0201 components will be used in more than one billion cell phones worldwide by the year 2003. Therefore, research and development on 0201 assembly is becoming a very hot topic. The first step to achieve a successful assembly process is to obtain a good PCB design for 0201 packages.

This paper presents the data and criteria of PCB design for 0201 packages, including the pad design for 0201 components, and the minimum pad spacing or component clearance between 0201 components or between 0201 and other components. A systematic study on pad design and pad spacing was undertaken, using two test vehicles and three Design of Experiments (DOEs). In the first DOE, 2 out of 18 types of 0201 pad designs were selected based on process yield. The second DOE was focused on pad spacing, including 10mil, 8mil, 6mil and 4mil. The third experiment was final optimization, using two types of optimized pad designs with 10mil, 8mil and 6mil pad spacing. Through the above experiments, the design guideline for PCB layout for 0201 packages and the assembly process capability are identified.

METHODOLOGY
The objectives for the 0201 project was to understand the assembly process capability of the existing machine, identify the critical process parameters/process window, and eventually establish 0201 factory implementation guidelines. Aiming to include the most critical factors in the investigation, the study started with a fishbone analysis. The main factors related to the 0201 assembly process were summarized into 10 categories, consisting of PCB design, component, stencil, solder paste, PCB handling, printing, pick and place, reflow, rework/touch-up, and inspection.

To identify the key parameters of 0201 pad design, two DOEs were undertaken: DOE1 for pad size identification, and DOE2 for pad spacing identification. DOE1 was based on selected process parameters in pick-and-place and reflow, and with the feedback data of the defect percentage after reflow. The criterion for DOE1 was that a pad design, which gave the lowest defect percentage with all different pick-and-place and reflow settings, would be the most robust 0201 pad design for production applications. DOE2 was focused on four types of pick-and-place machines and process evaluations on solder paste with a fillet-less pad. The results from both DOEs contributed to the final design of the assembly qualification vehicle.

DOE 1: PAD SIZE IDENTIFICATION
Test Vehicle Design
Based on existing pad design information from machine and component suppliers, 18 types of pad size with rectangular, round or home-based shape were designed. Test vehicle design DOE is provided in Table 1.

Materials and Tooling
Non-clean solder paste with mesh size of 25µm to 38µm and 90.25% of metal content (by weight) was utilized in this study. One type of 0201 resistors was used in this test.

The stencil was made by laser-cut with polish technology. For each type of pad design on this stencil, the aperture openings have the same shape as the pad, at 80%, 100% and 120% of the pad size, giving area ratios from 0.33 to 0.94.

Experimental
The printer and pick-and-place machine were calibrated and optimized before performing the experiment. The pick-and-place and reflow DOE is presented in Table 2.

Results and Discussion
The pad design selected was based on printability and the number of defects. Since the area ratio of 0.6 is the lowest ratio for acceptable printing and overprint is not recommended for the 0201 package [1], pad size 4, which is a filletless type pad design, is excluded due to poor printability. The number of defects observed on assembled boards were compared and plotted in Figure 1.

Based on the results, the pad design of modified pad size 1, pad size 3 and pad size 6 with NSMD were selected as candidates for qualification. More information about experiment, discussion and observations for pad size selection and process optimization was described in detail in reference [2].

Table 1. Pad design for 0201 package

Group	Item	Pad Name	SMD[1]	via	Orientation	Pad Area[2]	Pad Gap[3]
Rectangular	1	Pad 1	SMD	Y/N	0, 90	S	S
	2	Pad 1	NSMD	Y/N	0, 90	S	S
	3	Pad 2	SMD	Y/N	0, 90	M	M
	4	Pad 2	NSMD	Y/N	0, 90	M	M
	5	Pad 3	SMD	Y/N	0, 90	L	L
	6	Pad 3	NSMD	Y/N	0, 90	L	L
	7	Pad 4	SMD	Y/N	0, 90	Filletless	S
	8	Pad 4	NSMD	Y/N	0, 90	Filletless	S
Round	9	Pad 5	SMD	Y/N	0, 90	S	S
	10	Pad 5	NSMD	Y/N	0, 90	S	S
	11	Pad 6	SMD	Y/N	0, 90	M	S
	12	Pad 6	NSMD	Y/N	0, 90	M	S
Home-based	13	Pad 7	SMD	Y/N	0, 90	L	S
	14	Pad 7	NSMD	Y/N	0, 90	L	S
	15	Pad 8	SMD	Y/N	0, 90	M	M
	16	Pad 8	NSMD	Y/N	0, 90	M	M
	17	Pad 9	SMD	Y/N	0, 90	S	L
	18	Pad 9	NSMD	Y/N	0, 90	S	L

(1) SMD refers to Solder Mask Defined, and NSMD refers to Non-Solder Mask Defined.
(2) Pad Area refers to the area of rectangular, round or home-based pad. S=small; M=medium; L=large; Filletless refers to the pad being smaller than component dimension, and after assembling, the pad is invisible.
(3) Pad Gap refers to the pad spacing within the same 0201 component. S=small; M=medium; L=large.

Note: "Small", "Medium" and "Large" are defined within each pad-shape group.

Table 2. DOE Conditions for Pick-and-Place and Reflow

Run #	Mounting Pressure	Ramping Rate	Soak Time	Peak Temp.
1	5N	0.8 °C/s	60 sec	210 °
2	5N	1.25 °C/s	70 sec	220 °
3	5N	1.5 °C/s	80 sec	230 °
4	4N	0.8 °C/s	70 sec	230 °
5	4N	1.25 °C/s	80 sec	210 °
6	4N	1.5 °C/s	60 sec	220 °
7	2.5N	0.8 °C/s	80 sec	220 °
8	2.5N	1.25 °C/s	60 sec	230 °
9	2.5N	1.5 °C/s	70 sec	210 °

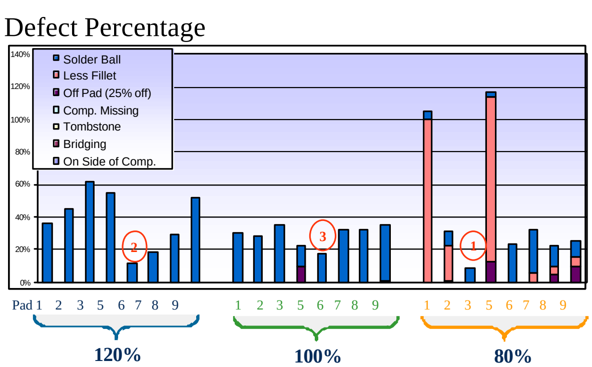


Figure 1. Percentage for each type of defects for different pad and stencil designs.

DOE 2: PAD SPACING IDENTIFICATION

Test Vehicle Design

A test vehicle, shown in Figure 2, was designed for the pick-and-place process evaluation for the 0201 package. This is a 6-layer FR4 board with a Ni/Au surface finish. There are a total of 4 boards in a panel, with outside dimensions of 3.5" X 1.4" for each board and 5" X 7" for the panel. A total of about 13,000 0201 locations, 100 0805 locations, 4 SOIC8 locations and 2 CSP locations were designed in this board.

As shown in Figure 3, Boards A, B and D were designed for spacing test between 0201 and 0201; and Board C was designed for spacing test between 0201

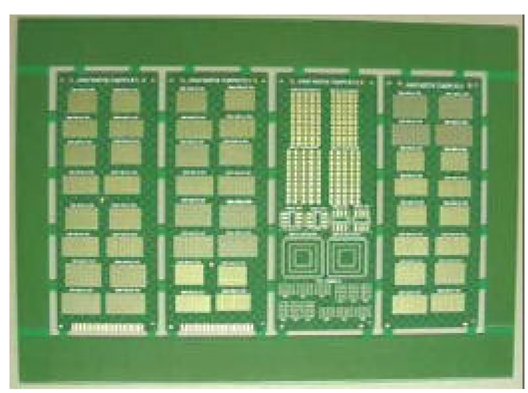


Figure 2. Test vehicle for pick-and-place process investigation.

components and other packages, such as CSP, SOIC and 0805.

On Board A, there were 4 test-groups, which were illustrated in figure 3 with different colors. Each color or test-group represents certain spacing among 0201s, including 0.20mm, 0.15mm, 0.125mm and 0.10mm. Each test group consists of 4 test-boxes, and each test-box has 250 locations for 0201 components. The differences among these 4 test-boxes are component orientation and the pad-defining method (SMD or NSMD). In each test group, there are a total of 1,010 0201 locations, including 250 locations of vertical SMD pads, 255 locations of horizontal SMD pads, 250 locations of vertical NSMD pads, and 255 locations of horizontal NSMD pads. Therefore, in Board A, more than 4,000 locations for 0201 components were designed.

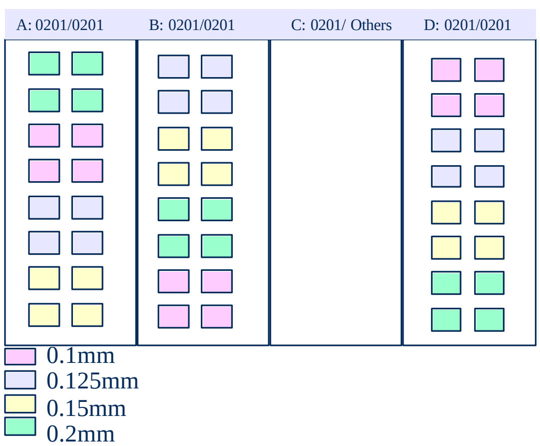
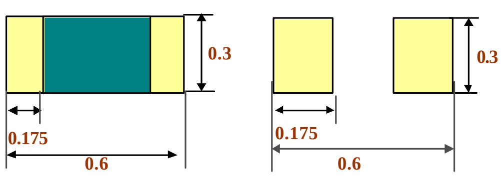


Figure 3. Map for spacing test of 0201 components.



(a) (b)

Figure 4. (a) Dimensions for 0201 components (b) Pad design for 0201 components in this test vehicle. (Unit: mm)

For Boards B and D, the same design method was utilized as board A, except that the locations for each test group was different. For example, the 4 pink test-boxes for 0201 components with 0.10mm spacing were located in the middle of Board A, the same 4 pink test-boxes were close to the bottom edge in Board B, and close to the top edge in Board D.

The dimensions for 0201 component and pad size are provided in Figure 4. As shown in Figure 4, the outside dimensions for 0201 pads and 0201 components were the same. This pad design allows the pick-and-place machine to place 0201 components as closely as possible. In other words, it was able to deliver the information about the pick-and-place machine capability of placement density for 0201 components.

Materials and Tooling

The same no-clean solder paste as in DOE1 was used for DOE2. One type of 0201 resistors and one type of 0201 capacitors were equally used in this test.

Experimental

<u>Procedure</u>

The experimental procedure was established before implementation. There were 3 runs included in this experiment. As shown in Table 3, in Run #1, 3 panels were printed with the optimized printer setting. After printing, sample panel #1 was taken out of testing for data collection. Then sample panels #2 and #3 went through pick-and-place with optimized machine setting, and after placement, sample panel #2 was taken out of testing for data collection. Then sample panel #3 was reflowed with an optimized reflow profile. After reflow, inspection and data collection were performed on sample panel #3.

For Runs #2 and #3, the same procedure was repeated. Data obtained included printing quality information from 9 panels after printing, pick-and-place information from 6 panels after placement, and assembled information from 3 panels after reflow.

With the above procedure, the assembly process with the defect level of 200 per million can be tested with 90% confident

<u>Assembly</u>

Four different production assembly lines, which have 4 different types of pick-and-place chip shooter machines, were tested at 4 different factory locations, using the same experiment procedure.

At the beginning of each experiment, the printer and the

Table 3. Experimental procedure for DOE2

Run#	Sample #	Printing	Data Collection	Pick-and-Place	Data Collection	Reflow	Data Collection
Run #1	#1	X	X				
	#2	X	X	X	X		
	#3	X	X	X	X	X	X
Run #2	#4	X	X				
	#5	X	X	X	X		
	#6	X	X	X	X	X	X
Run #3	#7	X	X				
	#8	X	X	X	X		
	#9	X	X	X	X	X	X

pick-and-place machine were calibrated and optimized for the 0201 test vehicle. In addition, the placement accuracy for each pick-and-place machine was tested by comparing the real placement data with the original CAD data. The pick-and-place machine was not considered ready for the main experiment until the CpK of the X, Y and θ deviation was equal or higher than 1.30.

Coordinate Measurement Machine Evaluation

The machine for placement deviation measurement was evaluated by performing the Gauge Repeatability and Reproducibility (GRR) study. The GRR data for all of the machines used for this study was lower than 30%, which is acceptable for this application. The data obtained from each measurement machine was listed in Table 4.

Results and Discussion

Printing

After printing, visual inspection was performed and recorded. There are mainly two types of defects: missing solder paste and insufficient solder paste (defined as less than 50% of average solder paste volume). The data obtained from four locations is summarized in Table 5. Under optimized printing conditions, the printing process reached a similar defect level at each location.

Pick-and-Place

During the pick-and-place process, the pick-up rate for each machine was collected and presented in Table 6. After pick-and-place, the X and Y placement accuracy on each board was measured by using the coordinate measurement machines listed in Table 4. The Cp and CpK data for the X and Y measurement were also provided in Table 6. The data, obtained from visual inspection on each board after placement, was included in Table 6 as well. As shown in Table 6, all of the CmK data were much higher than the CpK. Since CpK is measured from components on solder paste, it reflects the true process capability of the pick-and-place machine. As can be seen, all of the CpK data in Table 5 are higher than 1.00 and all of the pick-up rates were better than 99.8%.

As can be seen from Table 7, the defect distribution was different on different machines. No missing component was observed on pick-and-place machine A, and many billboards were observed on pick-and-place machine D. The reason may be that machine A has the pressure control system which can control the distance between the component and the solder paste for each placement, while other machines control the maximum pressure or the mounting height. Machine D does not check the thickness of the component; therefore, even if the machine picks up a component on its side, it still places the component as is.

Capacitors versus Resistors

A typical diagram of CpK for 0201 capacitors and resistors is presented in Figure 5. The CpK in both X

Table 4. Data summary for Gauge R&R for each coordinate measurement machine used in the experiment

Factory Location	Coordinate Measurement Machine	Orientation	GR&R
Location A	Machine A	Placement X	6.11%
		Placement Y	5.50%
Location B	Machine B	Placement X	15.7%
		Placement Y	5.7%
Location C	Machine C	Placement X	12.4%
		Placement Y	3.9%
Location D	Machine D	Placement X	<10%
		Placement Y	<10%

Table 5. Summary of defect per million for each printing process

Factory Location	Printer	No. of Defects	No. of 0201 Locations	DPM
Location A	Printer A	11	24240	454
Location B	Printer B	74	154968	478
Location C	Printer C	38	158568	240
Location D	Printer D	32	72000	444

Table 6. Data summary of defect per million for each pick-and-place process

Factory Location	Pick&Place Machine	X-CmK	Y-CmK	X-CpK	Y-CpK	No. of 0201 Components Placed	Pickup rate	DPM
Location A	Machine A	>1.33	>1.33	1.52	1.54	10,368	99.80%	965
Location B	Machine B	1.81	3.08	1.18	1.31	78,087	99.99%	142
Location C	Machine C	3.5	2.71	1.22	1.12	69,478	99.84%	518
Location D	Machine D	1.77	1.37	1.28	1.09	72,000	99.81%	2472

CmK: machine capability as measured on double-sided tape.
CpK: process capability as measured on solder paste.
DPM: defect per million.
Pick-up rate: percentage of successful component pick-ups out of the number of pick-up attempts.

and Y directions for the capacitors were higher than that for the resistors, probably due to the difference in the dimensional accuracy. As can be seen from the typical pictures of 0201 capacitors and resistors (Figure 6), the edge of a 0201 capacitor is better defined than a 0201 resistor; therefore, although the same pick-and-place condition was utilized, the component position measured may be different due to the component dimensional distortion.

Spacing Between 0201 Components

The CpK of placement accuracy for 0201 components was calculated for different component spacings, and typical data are presented in figure 7. The CpK data obtained from each assembly line revealed that there was no obvious relationship between component spacing and CpK of placement accuracy, even down to 4 mil spacing between 0201 components (body to body). Figure 8 is an example of 0201 components on solder paste after pick-and-place with 0.1mm spacing.

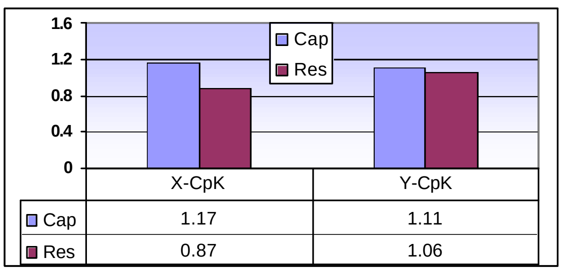
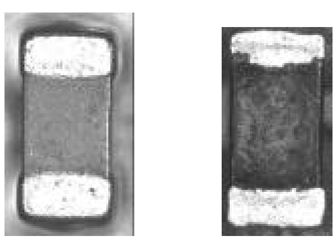


Figure 5. CpK in X and Y directions for 0201 capacitors and resistors after pick-and-place.



(a)0201 capacitor (b)0201 resistor

Figure 6. Typical pictures of 0201 capacitors and resistors used in the experiment.

Table 7. Defect distribution after pick-and-place at each factory location Unit: number of parts

Factory Location	Location A	Location B	Location C	Location D
Pick-and-Place Machine	Machine A	Machine B	Machine C	Machine D
Total Defects	10	10	36	178
Missing Component	0	5	14	3
Misalignment	10	4	15	116
Billboard	0	0	5	55
Others	0	1	2	4

Reflow

Typical DPM data after reflow for each spacing is provided in Table 8 including bridging, misalignment, solder balling, missing components, and tombstones. In order to reveal the difference between the different conditions, the criteria used in the inspection were more stringent than typically used assembly standards. Most of the solder balls exist next to components on SMD pads, and were excluded from Table 8 due to the high defect rate on SMD pads.

Besides solder balling, the main defect in Table 8 was bridging and component misalignment. Table 8 revealed that with the pad design, which has the same outside dimension as 0201 components, at 0.2mm spacing, the DPM is lower than 1000ppm. Once the spacing is closer than 0.2mm, the DPM increased rapidly, especially on SMD pads. Since bridging was the main issue when components got closer, the stencil design will be the key factor for assembly process with close spacings.

Assembly Qualification

Test Vehicle Design

A 0201 qualification vehicle was designed based on the results from DOE1 and DOE2. Two types of pad design with three types of pad spacing were utilized on this test vehicle (Figure 9). There are a total of 1,800 locations designed with pad U, which was modified from NSMD pad size 1 in DOE1, and another 1,800 locations for pad H, which was a NSMD pad size 6.

Experimental

A no clean solder paste (particle size 3 with mesh size of 25um to 45um) was used in this qualification experiment. An electroform stencil with 5mil thickness and 1:1 ratio between the aperture size to the pad size was utilized. The solder paste transfer ratio of 70% of theoretical volume was achieved. Two types of 0201 capacitors and two types of 0201 resistors were equally designed into the pick-and-place program. The same

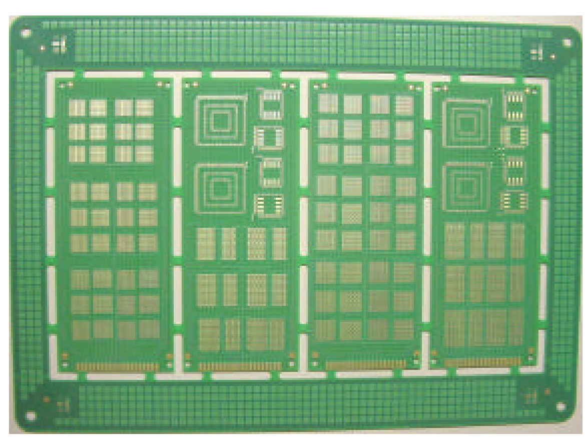


Figure 9. 0201 qualification vehicle

type of pick-and-place machine as used at location B in DOE2 was selected for this qualification experiment. A total of 38 panels were assembled with 22,800 locations for each type of pad spacing.

Results and Discussion

All assembled qualification boards were manually inspected under microscope after printing, pick-and-place, and reflow. Missing components was the main defect after pick-and-place. A typical picture of a location with missing components after pick-and-place was presented in Figure 10, showing that the component had been placed onto the solder paste but did not remain in place.

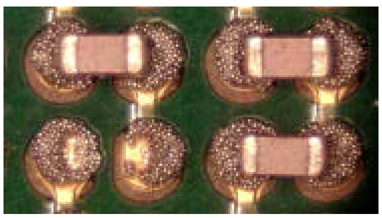


Figure 10. A location with a missing component.

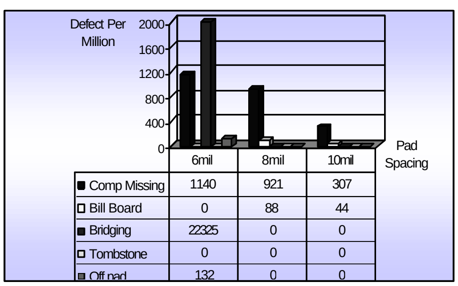


Figure 11. Defect per million for each type of defect for different pad spacing of pad U.

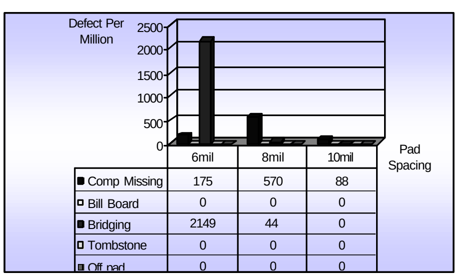


Figure 12. Defect per million for each type of defect for different pad spacing of pad H.

The defect per million after reflow for pad U and pad H was provided in Figure 11 and 12 respectively. As can be seen, the locations with 6mil pad spacing show the highest number of defects because of bridging. The defects observed on pad spacing of 8mil and 10mil were missing components and billboards.

Different stencil technology, solder paste, and components with tighter dimensional specifications (including components and pocket tape) have been used to significantly reduce defects, and this will be reported in a future publication.

SUMMARY

In this paper, data and criteria of PCB design for 0201 packages were presented, including the pad design for 0201 components, and the minimum pad spacing or component clearance between 0201 components or between 0201 and other components. A systematic study on pad design and pad spacing was undertaken using two test vehicles and three Design of Experiments (DOEs). In the first DOE, 2 out of 18 types of 0201 pad designs were selected based on process yield. The second DOE was focused on pick-and-place machine capability for different pad spacings, including 10mil, 8mil, 6mil and 4mil. The third experiment was final optimization, using two types of optimized pad designs with 10mil, 8mil and 6mil pad spacings. Through the above experiments, the design guideline for PCB layout for 0201 packages and the assembly process capability have been established.

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