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Board Design and Assembly Process Evaluation for 0201 Components on PCBs

Mei Wang, Dr. Dongkai Shangguan, David Geiger,
Kazu Nakajima, CC. Ho, and Sammy Yi
Flextronics
San Jose, CA

Abstract

As 0402 has become a common package for printed circuit board (PCB) assembly, research and development on mounting 0201 components is emerging as an important topic in the field of surface mount technology for PWB miniaturization. In this study, a test vehicle for 0201 packages was designed to investigate board design and assembly issues. Design of Experiment (DOE) was utilized, using the test vehicle, to explore the influence of key parameters in pad design, printing, pick-and-place, and reflow on the assembly process. These key parameters include printing parameters, mounting height or placement pressure, reflow ramping rate, soak time and peak temperature. The pad designs consist of rectangular pad shape, round pad shape and home-based pad shape. For each pad design, several different aperture openings on the stencil were included. The performance parameters from this experiment include solder paste height, solder paste volume and the number of post-reflow defects. By analyzing the DOE results, optimized pad designs and assembly process parameters were determined.

Introduction

Many challenges exist to successfully assemble a passive component as small as a 0201 onto a printed circuit board (PCB). These challenges included solder paste, printer, stencil design, solder paste measurement capability, pick-and-place machine, X/Y alignment measurement machine, reflow profile, rework station, automatic optical inspection machine, X-ray system, etc.

For example, 0402 components have a recommended rectangular pad design for manufacturing that is 18 mils by 20 mils. The acceptable accuracy of pick-and-place data supplied by the PCB designer is +/-0.5mil. However, for 0201 components, with outside dimensions of 12mils by 24mils, pad dimensions utilized can be as small as 12mils by 13mils, or even as small as 10mils by 6mils, and the spacing between 0201s shrinks to 6-8mils. In this case, the data accuracy for a pick-and-place machine has to be improved. For 0201 assembly, every 'mil' makes a big difference.

Although there are many important factors in the 0201 assembly process, this study is focused on pad design selection and process parameter optimization.

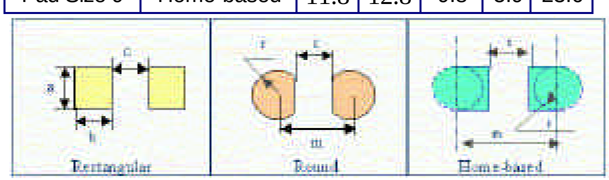
Experimental Set-up

Test Vehicle

To investigate the assembly process for 0201 components, a 0201 test vehicle was designed. After reviewing existing pad designs for 0201, the next step was to try and understand the relationship between pad design and assembly process parameters, with nine types of pad dimensions and eighteen types of pads with different pad shapes. The pad dimensions are provided in Table 1, and the features for each type of pad design are presented in Table 2. Table 2 illustrates that each type of pad design in turn includes via in pad, no via in pad, 0 degree and 90 degree to the longitudinal direction of the panel. More detailed descriptions of the test vehicle can be found in a previous paper.[1]

Table 1 – Pad Dimensions (Unit: mil)

Pad Size	Pad Shape	a	b	c	r	m
Pad Size 1	Rectangular	12.6	9.1	9.8		
Pad Size 2	Rectangular	16.1	9.8	12.2		
Pad Size 3	Rectangular	20.0	14.9	14.1		
Pad Size 4	Rectangular	10.2	5.7	10.6		
Pad Size 5	Round	11.8	11.8	9.8	5.9	21.7
Pad Size 6	Round	15.7	13.8	9.8	7.9	21.7
Pad Size 7	Home-based	11.8	15.8	3.9	5.9	23.6
Pad Size 8	Home-based	11.8	14.3	6.9	5.9	23.6
Pad Size 9	Home-based	11.8	12.8	9.8	5.9	23.6



Stencil Design

A laser-cut (with polish) stencil with 5mil thickness was consistently utilized in this test. While keeping the same shape with the pad, the dimension of the aperture openings were 120%, 100% and 80% of the pad size for each type of pad design. The area ratio (AR) at each aperture opening is listed in Table 2.

Table 2 – List of Pad Designs and Area Ratios

Pad Design on PCB						Area Ratio on Stencil		
Item	**Pad Name**	**Shape**	**SMD**	**Via-in-Pad**	**Orientation** (degree)	**Aperture Opening 120%**	**Aperture Opening 100%**	**Aperture Opening 80%**
1	Pad 1	Rectangular	SMD	Y/N	0, 90	0.58	0.53	0.47
2	Pad 1	Rectangular	NSMD	Y/N	0, 90	0.58	0.53	0.47
3	Pad 2	Rectangular	SMD	Y/N	0, 90	0.67	0.61	0.55
4	Pad 2	Rectangular	NSMD	Y/N	0, 90	0.67	0.61	0.55
5	Pad 3	Rectangular	SMD	Y/N	0, 90	0.94	0.86	0.77
6	Pad 3	Rectangular	NSMD	Y/N	0, 90	0.94	0.86	0.77
7	Pad 4	Rectangular	SMD	Y/N	0, 90	0.40	0.37	0.33
8	Pad 4	Rectangular	NSMD	Y/N	0, 90	0.40	0.37	0.33
9	Pad 5	Round	SMD	Y/N	0, 90	0.65	0.59	0.53
10	Pad 5	Round	NSMD	Y/N	0, 90	0.65	0.59	0.53
11	Pad 6	Round	SMD	Y/N	0, 90	0.86	0.79	0.70
12	Pad 6	Round	NSMD	Y/N	0, 90	0.86	0.79	0.70
13	Pad 7	Home-based	SMD	Y/N	0, 90	0.75	0.68	0.61
14	Pad 7	Home-based	NSMD	Y/N	0, 90	0.75	0.68	0.61
15	Pad 8	Home-based	SMD	Y/N	0, 90	0.71	0.65	0.58
16	Pad 8	Home-based	NSMD	Y/N	0, 90	0.71	0.65	0.58
17	Pad 9	Home-based	SMD	Y/N	0, 90	0.68	0.62	0.55
18	Pad 9	Home-based	NSMD	Y/N	0, 90	0.68	0.62	0.55

SMD: solder mask defined; NSMD: non-solder mask defined.
Area Ratio: ratio of aperture opening area to aperture wall area.

Solder Paste

A eutectic Sn/Pb, no-clean solder paste with 89.5% (by weight) metal content was used in this test. The mesh size is 400/+635, with solder powder diameters of 20-38 microns.

Components

Zero ohm 0201 resistors were used. The outside dimensions and their tolerances of the 0201 components are as follows:

- Length: 0.6mm ± 0.03m
- Width: 0.3mm ± 0.03mm
- Height: 0.23mm ± 0.03mm
- Terminal: 0.15mm ± 0.03mm

Experimental Work

Solder Paste Printing

Two DOEs were designed and performed to optimize the printer settings and to select a stencil and solder paste. Detailed descriptions of the DOEs can be found in a previous paper.[1] Important conclusions from these two DOEs are as follows:

1. Based on the results from the DOE on solder paste printing, low printing speed, low squeegee pressure and medium separation speed were employed during the test performed in this study.
2. When 60% solder paste volume release is used as the criteria, the minimum AR required for each type of pads/aperture, stencil technology and solder paste type is provided in Table 3. Overall, rectangular apertures have better release than home-based apertures, which, in turn, have better release than round apertures.
3. When the AR is between 0.47 and 0.55, electro-form (E-form) stencil with type 4 solder paste is recommended.
4. Pad 4 has an AR of 0.33-0.40, which is much lower than any recommended AR for both E-form stencil and laser-cut (with polish) stencil, for both type 3 and type 4 solder paste. Therefore, Pad 4 is excluded from further work due to printing difficulties.
5. Due to the existence of a solder mask on the edge of the pads on solder mask defined (SMD) pads, the solder paste height measured on SMD pads is about 0.5mil lower than that measured on non-solder mask defined (NSMD) pads. However, on SMD pads, the solder paste volume is about 20% more than on NSMD pads with E-form stencil and 14% more with laser-cut (with polish) stencil.

For this test vehicle, although the E-form stencil is recommended, the laser-cut (with polish) stencil was used for the experiment in this study due to aperture bridging observed on locations of Pads 7 and 8 on the E-form stencil.

Table 3 – Recommended Minimum Area Ratios for 60% Solder Paste Release

Pad Type	E-Form Stencil		Laser-Cut with Polish Stencil	
	Type 3	Type 4	Type 3	Type 4
Rectangular Pads	0.58 to 0.61	0.58 to 0.61	0.58 to 0.61	0.58 to 0.61
Round Pads	0.75	0.63	0.7	0.7
Home-based Pads	0.65	0.65	0.66	0.66

Therefore, for solder paste printing, laser-cut (with polish) stencil with 5mil thickness, and type 4 solder paste were utilized for this experiment. The printer setting was low printing speed, low squeegee pressure and medium separation speed. 27 panels were printed under each printing condition.

Pick-and-Place and Reflow

The pick-and-place machine was calibrated just before the experiment. After solder paste printing, the components were placed and the boards were reflowed under different assembly conditions. These assembly conditions were designed as a DOE and presented in Table 4. The assembly test was performed within one day without interruption.

The sample size (i.e. number of 0201 components) on each panel was 40 for each type of pad size and aperture opening. Three panels were printed under each assembly condition, giving a total sample size of 120 for each condition. 27 panels were assembled for the entire DOE, giving 58,320 assembled 0201 resistors, with 29,160 locations on SMD pads and the other 29,160 locations on NSMD pads.

Table 4 – DOE Conditions for Pick-and-Place and Reflow

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

Results and Discussion

Inspection

After reflow, all the sample boards were inspected under a microscope, and the number of defects for each location was collected.

Defects observed after reflow included solder balling, component off-pad/skewing, insufficient solder fillet, tombstoning, missing component, component mounted on side, and bridging. The main defect found in this experiment was solder balls, especially with SMD pads.

Solder Balls

Since the most serious defect observed was solder ball defect, to understand the root cause of this type of defect, analysis was undertaken at the early stage of data analysis.

The first comparison was performed on the number of defects between the SMD pads and the NSMD pads, regardless of pad size, via or no via, component orientation and aperture opening size on stencil. The solder balls were counted and summarized only based on SMD and NSMD (Figure 1). It can be seen that the number of solder balls observed on the SMD pads was at least twice as many as on the NSMD pads. This is believed to be due to the different solder paste volume. As indicated previously, on the same test vehicle, there was about 14% more solder paste volume on SMD pads than on NSMD pads,[1] as shown in Figure 2.

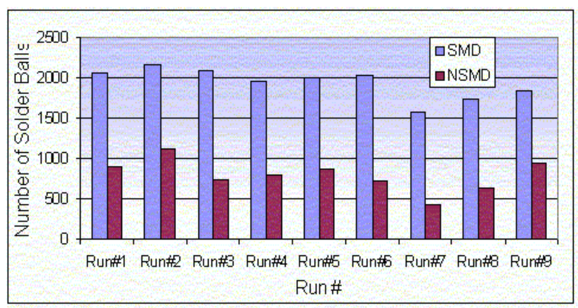


Figure 1 – The Number of Solder Ball Locations for Different Runs in the DOE – A Location with One or More Solder Balls was Counted as One Solder Ball Location

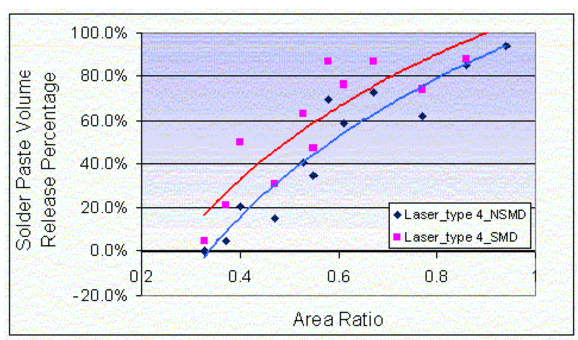


Figure 2 – Solder Paste Volume Release Percentage versus AR on Stencil

To find out if it would be possible to solve the solder balling issue by using different process parameters, additional comparison between SMD pads and

NSMD pads was performed. The lowest percentage of solder balls under different process conditions (as listed in Table 4) was presented in Table 5. It can be seen from Table 5 that, regardless of process conditions, solder balls predominantly existed on SMD pads. As compared with SMD pads, NSMD pads had a wider process window regarding solder balls. Consequently, further investigation was focused on NSMD pads only.

Table 5 – Comparison of the Lowest Number of Solder Balls on SMD and NSD Pads

	SMD		NSMD	
	Lowest Solder Ball %	Pad Size	Lowest Solder Ball %	Pad Size
Run #1	13.3%	Pad 6	0.0%	Pad 1
Run #2	18.3%	Pad 7	6.7%	Pad 5
Run #3	18.3%	Pad 7	0.0%	Pad 5
Run #4	8.3%	Pad 7	1.7%	Pad 5
Run #5	15.0%	Pad 6	3.3%	Pad 1
Run #6	8.3%	Pad 6	0.0%	Pad 1,2,5
Run #7	3.3%	Pad 7	0.0%	Pad 1,3,5
Run #8	8.3%	Pad 7	0.0%	Pad 2
Run #9	16.7%	Pad 3	1.7%	Pad 3

* Not including pad 4

Pad Design Optimization

To select an optimized pad design, all types of defects were summarized in Figures 3 and 4. In Figure 3, Pad 3 with 80% aperture opening on stencil shows the lowest defect percentage, followed by Pad 6 with 120% and 100% aperture opening on stencil. Overall, Pad 6 has the lowest defect rate.

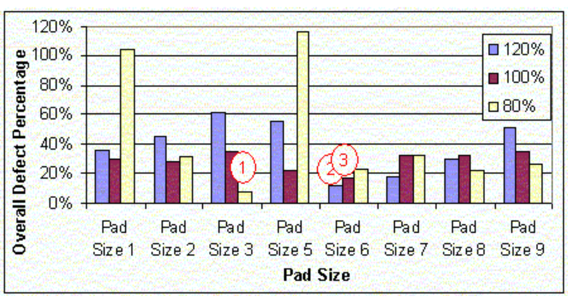


Figure 3 – Defect Percentage for Each Type of Pad Design, Stencil Design, Pad Size and Stencil Aperture Opening

Figure 4 shows that solder ball is the No. 1 defect in this experiment. Figure 4 also shows that, unlike other pad designs and aperture openings, the main defect on Pads 1 and 5 with 80% aperture opening is insufficient solder fillet. However, excluding the insufficient solder defect, Pad 1 gave the lowest defect percentage among all the different combinations of pad sizes and aperture openings. Thus, with improvement in solder paste volume, Pad 1 does have the potential to be one of the candidates for pad design for 0201 components.

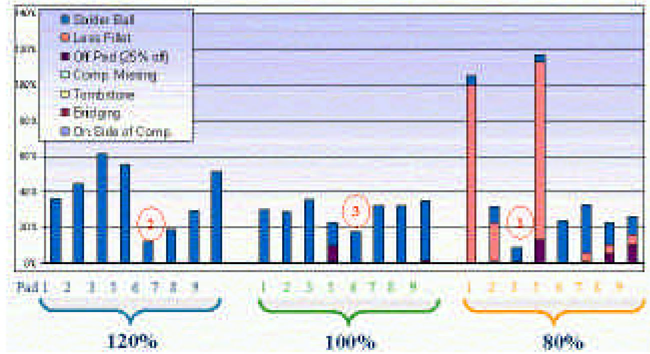


Figure 4 – Percentage for Each Type of Defect for Different Pad Designs and Stencil Designs

Typical pictures for each type of defect were shown in Figure 5. The specification used for component-off-pad was 25% of component width or component metal terminal hanging out of pad. The specification for insufficient solder fillet was the height of solder joint lower than 50% of component height (which is more stringent than the IPC610C requirement).

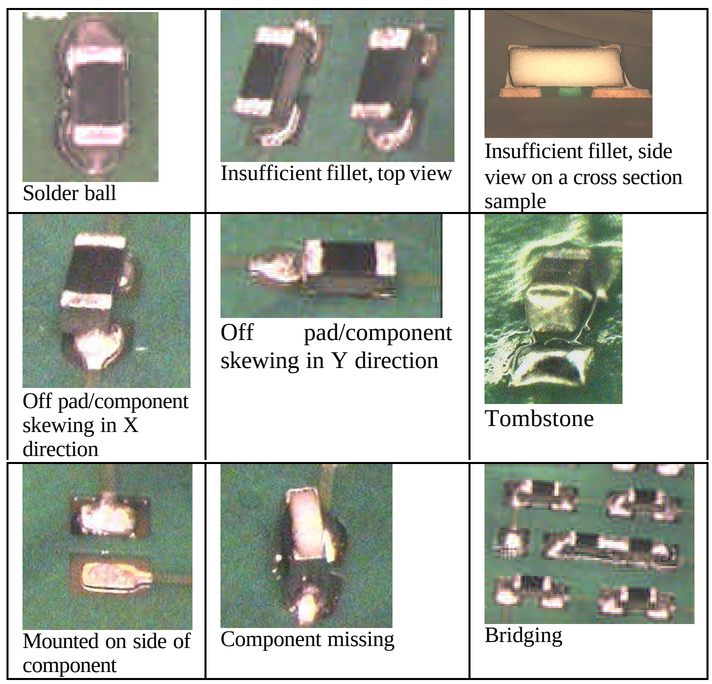


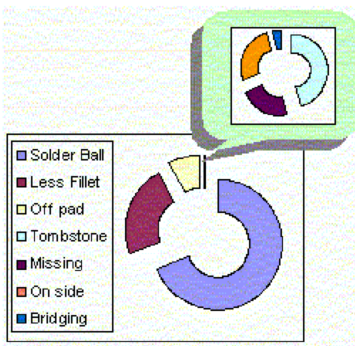
Figure 5 – Typical Defects

Based on the analysis above, Pads 1, 3 and 6 were selected for further study.

Defect Distribution

The defect distribution is not uniform. There are 7,713 out of 29,160 (i.e. 26.45%) assembled locations that had solder ball defect. 2,580 out of 29,160 (i.e. 8.85%) assembled locations had the defect of insufficient fillet. The third major type of defect was component-off-pad, in which there were 881 (i.e. 3.02%) assembled locations with components off pad by more than 25% of the component width. The rest of the defects were 12 tombstones (0.04%), 6 component missing (0.02%), 7 mounted on side of component (0.02%), and 1 component bridging (0.003%).

As shown in Figure 6, about 68.86% of defects were solder ball and 23.04% defects were insufficient fillet. Both solder ball and insufficient fillet can be improved by optimizing stencil design and/or solder paste selection. As shown in Figure 4, with the aperture opening reduced from 120%, to 100% and to 80%, the solder ball defect percentage decreased. This fact was observed on most of the pad sizes, except Pad 6. One objective for future experiment will therefore be to reduce solder ball defect in 0201 assembly processes.



Defects	Percentage
Solder Ball	68.86%
Insufficient Fillet	23.04%
Off pad	7.87%
Tombstone	0.11%
Missing	0.05%
On side	0.06%
Bridging	0.01%

Figure 6 – Defect distribution Map

Instead of using the IPC specification for off-pad, which is 50% hanging over as a defect, a tighter specification (25%) was utilized when counting off-pad defects in this experiment, resulting in 7.87% off-pad defects. Using a tighter specification helped reveal the alignment issue for pick-and-place. Since the purpose of this experiment was focused on pad design selection, pick-and-place and reflow process optimization, the spacing among components was 0.5mm. The only bridging observed in this experiment (0.01%) most likely came from a pick-and-place error. Smaller component spacing, such as 0.2mm or even 0.125mm, has already been designed into future experiments.

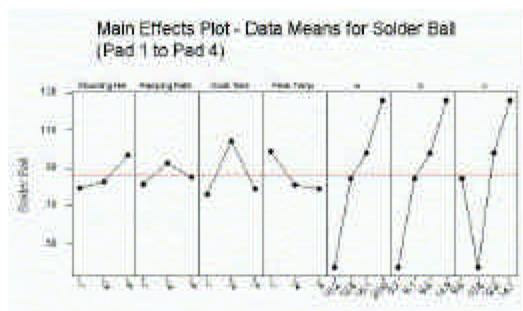
Overall, solder balls were identified as the primary defect. Due to the overwhelming amount of solder balls observed, over-print is not recommended for most of the pad designs. Pick-and-place alignment consistency is the second issue observed during data analysis. Therefore, alignment monitoring during assembly process is recommended. To simulate the real production environment, component spacing should be varied in future experiments.

Pick-and-Place and Reflow Process Optimization

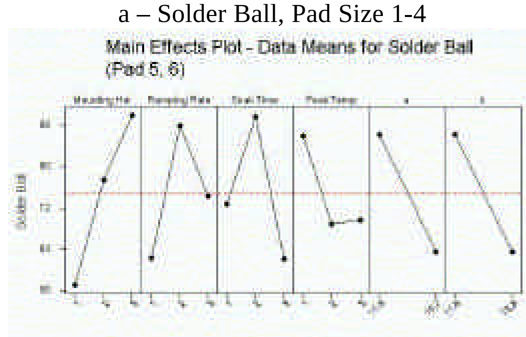
To understand the relationship between process parameters and each type of defects after reflow, the defects were analyzed for each of the variables, including: (1) mounting pressure; (2) temperature ramping rate; (3) soak time; (4) peak temperature during reflow; (5) pad dimension, **a** (Table 1); (6) pad dimension, **b** (Table 1); and (7) gap between two pads within one component, **c** (Table 1). The analysis was performed for different pad shapes.

Solder Ball

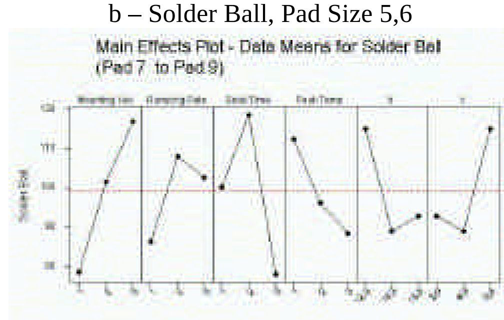
The results from the main-effects-analysis for solder balls are shown in Figure 7. Based on the analysis for process parameters, low mounting pressures and high peak temperatures are recommended on all types of pads to reduce solder balls. For pad design, on rectangular pads, the most important factors are pad size **a** & **b** and the aperture size on stencil. The amount of solder ball defects decreased when the pad size was decreased.



a – Solder Ball, Pad Size 1-4



b – Solder Ball, Pad Size 5,6

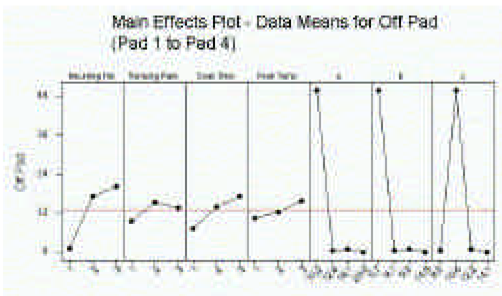


c – Solder Ball, Pad size 7-9

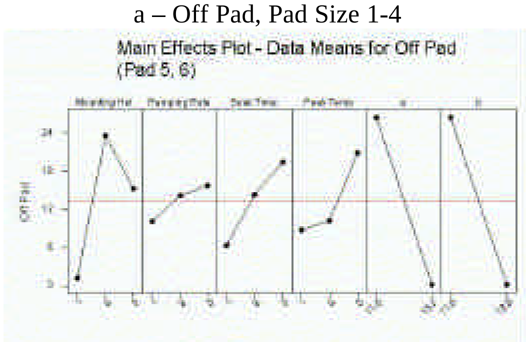
Figure 7 – Main-Effects-Analysis on Solder Bal Defects

Off-Pad/Skewing

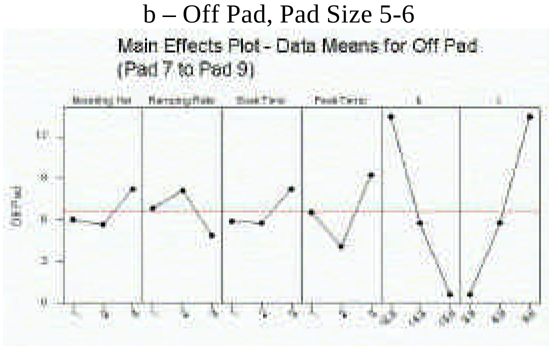
The results from the main-effects-analysis for off-pad and skewing are shown in Figure 8. For process parameters, low mounting pressures, low ramping rates, low soak time, and low peak temperatures are recommended on all types of pads to reduce the number of components hanging off pad. Figure 9 illustrates the number of off-pad defects for the different runs (Table 4). It is evident from Figure 9 that the last three runs, with the lowest mounting pressure of 2.5N, have the lowest amount of off-pad defects.



a – Off Pad, Pad Size 1-4



b – Off Pad, Pad Size 5-6



c – Off Pad, Pad Size 7-9

Figure 8 – Main-Effects-Analysis on Off-Pad Defects

For pad design, large pad sizes (**a** and **b**) are recommended. However, the trend for dimension **c** is not very clear from the analysis.

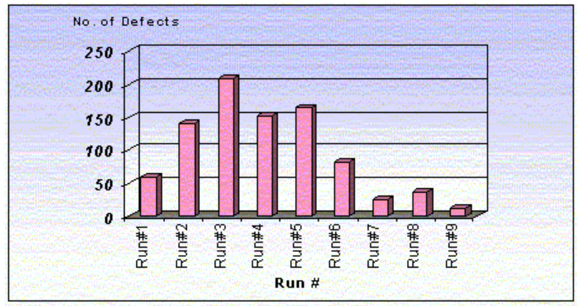
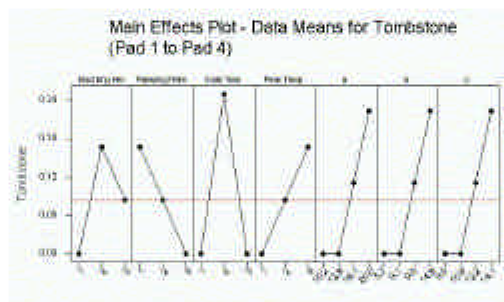


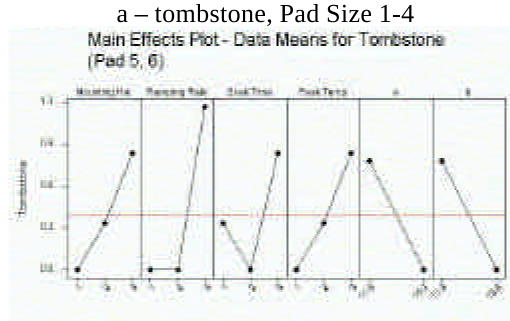
Figure 9 – Number of Off-Pad/Skewed Defects for Different Runs

Tombstoning

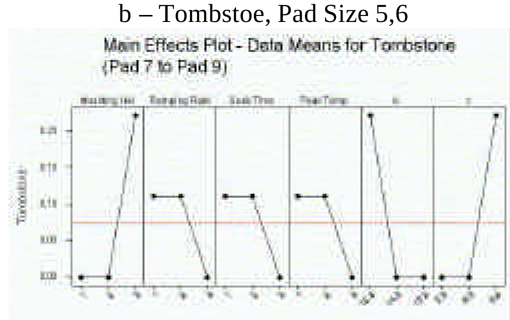
Figure 10 shows the main-effects-analysis for tombstoning. For process parameters, on all types of pad, low mounting pressures are recommended to reduce the amount of tombstone defects. For pad design, on rectangular pads, small pad sizes (**a** and **b**) are recommended. However, on round and home-based pads, large **a** and **b** are recommended. In addition, for all types of pad design, small **c** will reduce tombstoning.



a – tombstone, Pad Size 1-4



b – Tombstoe, Pad Size 5,6



c – tombstone,Pad Size 7-9

Figure 10 – Main-effects-Analysis on Tombstone Defects

Figure 11 illustrates the number of tombstoning defects for different runs (Table 4). It can be see from Figure 11 that the last three runs (with the lowest mounting pressure of 2.5N) have the lowest amount of defects.

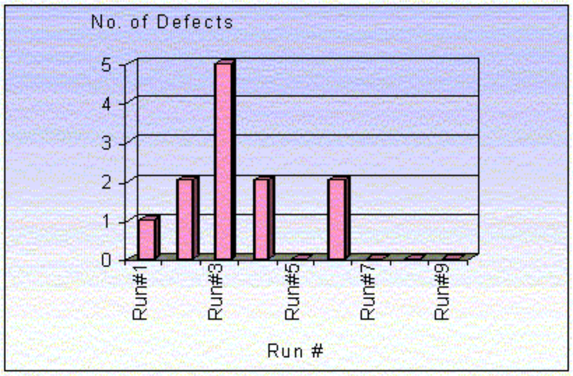


Figure 11 – Number of Tombstone Defects for Different Runs

The number of tombstone defects versus pad gap, ***c***, was provided in Figure 12. The two highest defect data points in Figure 12, when ***c***=0.25mm, were due to pick-and-place alignment issues on two of the panels. When dimension ***c*** is smaller than 0.25mm, no tombstone defect was observed in any of the runs. Therefore, dimension ***c*** larger than 0.25mm is not recommended.

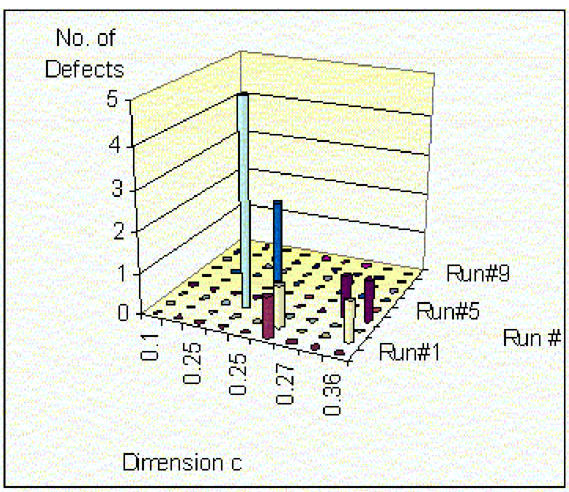
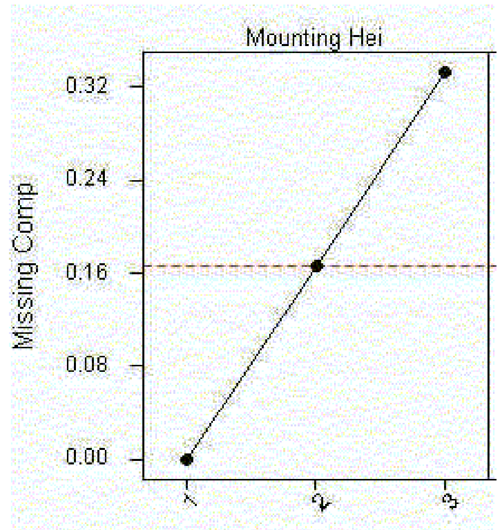


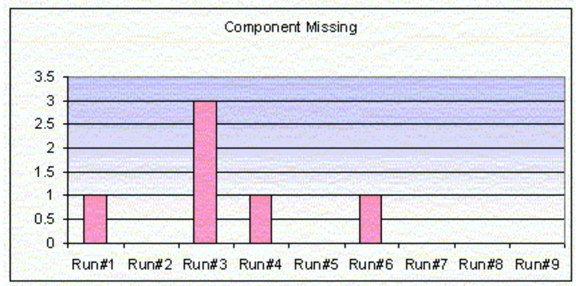
Figure 12- Number of Tombstone Defects for Different Process Conditions and Pad Gap

Missing Components

As shown in Figure 13(a), a very small number of missing components was observed at low mounting pressures. Figure 13(b) shows that the last three runs, with the lowest mounting pressure, show no missing components. Therefore, a low mounting pressure is recommended to avoid component missing. Figure 14 shows that when the pad gap, **c**, was increased, the number of missing components increased as well. As a result, the pad gap, **c,** larger than 10 mils, is not recommended.



(a)



(b)

Figure 13 – (a) Number of Missing Components versus Mounting Pressure (b) Number of Missing Components for Different Process Conditions

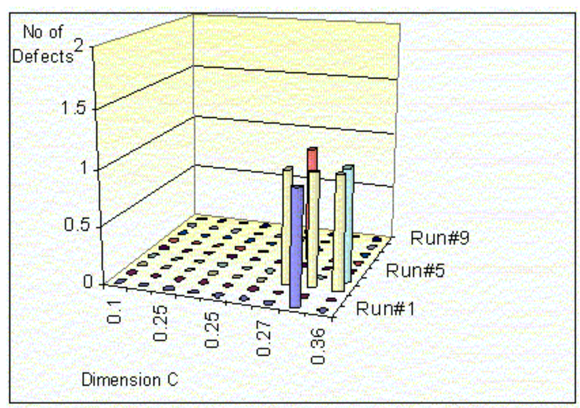


Figure 14 – Number of Missing Component for Different Process Conditions and Pad Gap, C

Via-In-Pad

Voids were observed in the solder joints after the assembly process, using X-ray inspection (Figure 15) and cross-sectioning (Figure 16). Overall, the size of voids was comparable to the size of the via. In Figure 15, a void can be seen in the left solder joint, while the micro-via underneath the right solder joint was filled by solder. In Figure 16, a void can be seen in the right solder joint just above the micro-via, while the micro-via underneath the left solder joint was filled by solder. The right side of the component was lifted due to the void underneath.

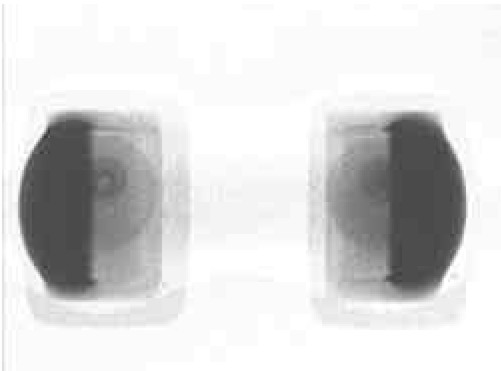


Figure 15 – An X-ray Picture Taken from a Soldered Component on its Pads with Micro-Via Pad

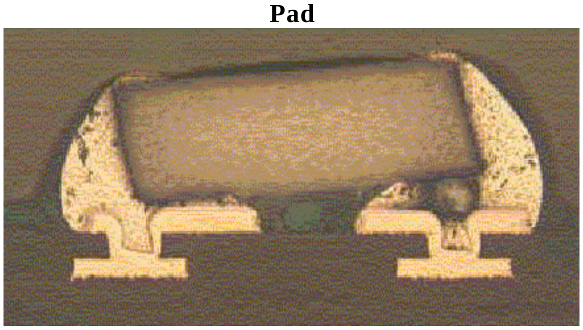


Figure 16 – Cross-Section Picture Taken from a Soldered Component on its Pads with Micro-Via in Pad in the right Solder Joint

Summary

In this work, the influence of key process parameters and pad design on the number of defects for 0201 assembly was studied in detail. It has been found that NSMD pads have a wider process window than the SMD pads with regard to solder balls. Other major defects observed were off-pad/skewed components and insufficient fillet. By comparing the total number of defects for each type of pad design and stencil design, Pads 1 and 6 have been selected for further study.

The assembly process conditions have been found to have significant impact on the number of each type of defects. Since solder balling was the primary defect in this test, over-print is not recommended for stencil design for 0201 components. It has also been revealed that the mounting pressure during component pick-and-place is a very important process parameter, and a low mounting pressure is recommended. Component alignment during pick-and-place is another important factor. The overall recommendations are summarized in Table 6.

Table 6 – Summary of Recommendations

Rectangular	**Mounting Pressure**	**Ramping Rate**	**Soak Time**	**Peak Temp.**	**a**	**b**	**c**
Missing Comp.	L*			L*			L*
Off Pad	L*	L	L	L	H*	H*	
Solder Ball	L			H	L*	L*	
Tombstone		H*		L*	L*	L*	L*
Round & Home base	**Mounting Pressure**	**Ramping Rate**	**Soak Time**	**Peak Temp.**	**a**	**b**	**c**
Missing Comp.	No Missing Component						
Off Pad	L	L	L	L	H	H*	L*
Solder Ball	L*	L	H	H*	H		H
Tombstone	L*	L*		L	H	H*	L

* Denotes a very significant factor

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Reference

1. Mei Wang, David Geiger, Kazu Nakajima, Dr. Dongkai Shangguan, C. C. Ho and Sammy Yi "Investigation of Printing Issue and Stencil Design for 0201 Package" *SMTA, 2001, Chicago*