Broadband Printing – A Paradigm

Arun S. Ramasubramanian, Dr. Daryl Santos, Suny Binghamton
Binghamton, NY 13902-6000
Dr. Rita Mohanty
Speedline Technologies, Franklin, MA,

Abstract
The SMT industry is going through a challenging phase of assembling miniature components, such as micro BGA, 0.3mm CSP and 01005 passives onto Printed Circuit Boards (PCB). This effort is primarily driven by the cell phone and other hand held device industries due to consumer demand for smaller devices with more functionality. Other industries, such as those that supply the defense and those in medical electronics, among others, are also expected to start using such miniature components in the near future. Because these miniature components require solder deposits that are significantly smaller per pad than other components that will reside on the same circuit board, such as QFPs, PLCC's, there arises a challenge in SMT assembly to satisfactorily deposit solder paste for all components on the PCB.

As such, a term has arisen in the industry that has lately been used to describe this "one size fits all" process; that term is "Broadband Printing". Broadband Printing refers to a robust printing process that provides stable process parameters that can print from the smallest to the largest pad in a single assembly with equally satisfactory results.

This paper presents the analysis from a recent printing study employing a test vehicle that includes components such as 01005s to QFPs. In a recent publication, part of this study was presented focusing on 01005 printing only. This printing process was determined to be suitable for 01005s assembly and also analyzed based on statistical capability. The current paper will present the results from additional detailed analysis to determine if this process has the capability to provide sufficient solder paste deposits for larger components located on the same test board. In the future, the SMT industry may always look towards "Broadband Printing" as an alternative to dual stencil or stepped stencil printing technologies in order to meet the needs of both small and large components.

Key words: Process Capability, Stencil Printing, 01005, Pb-Free, Broadband Printing, Solder Joint Strength.

Introduction
From 1206 to recently arrived 01005 there has been a natural size reduction of passives. The necessity to accommodate smaller passives on the circuit boards that also must contain various other, larger components has become a necessity owing to the increasing demands from the Industry[1] . The components such as 01005 help in enhancing the electrical performance by the reduction of electrical distances and increased densities [2], along with reducing the real estate requirement in the circuit board. However, developing a robust printing and reflow process has continued to be a major challenge plaguing the industry with diverse opinions and challenges[3,4] . This paper is the first step in understanding and creating a robust assembly process – one that accommodates all the components' performance metrics as deemed necessary.

Discussion of Methodology
The paper derives its basis from previous work that was presented else where[4,5,6] .This section will briefly cover the test vehicle design, Gage R&R, experimental design and treatment combination used in this analysis. The data used for the analysis is from the four run orders of the DOE where physical setting for the experiment were the same (Stencil, Paste Type) and the process had variations that include squeegee speed, wipe method and squeegee pressure.

Since the focus of the previous DOE was to understand the paste transfer efficiency (TE), only volume transfer efficiency data was collected for analysis. Transfer efficiency data certainly tells us if the TE efficiency for larger components were as good as the miniature components but it doesn't tell us anything about the mechanical integrity of the components. In another word, it doesn't tell if the volume of paste delivered for the larger component is adequate to provide enough mechanical strength to hold the component in place. To understand this aspect of the process, conventional shear testing method was employed to evaluate bond strength of both miniature and larger components. The components were shear tested using the DAGE 4000 shear tester and provides a basis to understand the absolute performance of the solder joints after reflow.

Test Vehicle
The test vehicle used in this study is a four layer FR-4 board measuring 10" x 8" x 0.062" (L x W x T) with a Ni-Au pad surface finish and is shown in Figure 1.This test vehicle has different types of small pads (including those of 0201 and 01005)

as well as larger component pads that are widely used in the electronics manufacturing industry. The components -boxed in the yellow line refer to the components used for this study.

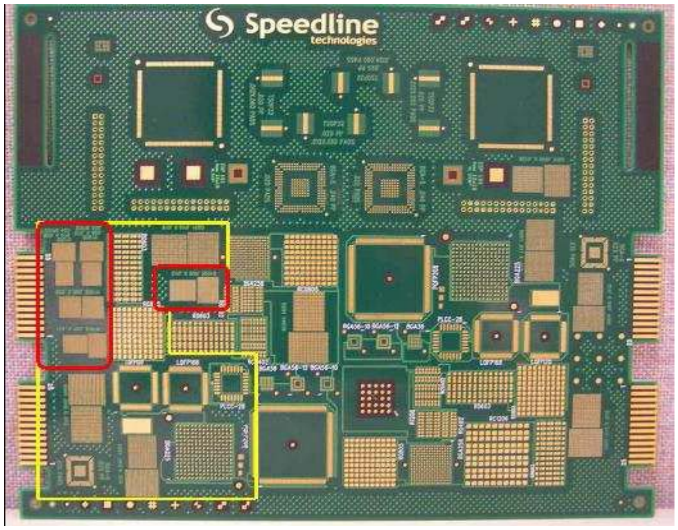

Figure 1. Test Vehicle

Stencil and pad geometry

The different pads used in the analysis have a stencil opening on a 1:1 ratio. Thus theoretically the volume transferred to the pads must be the area of the pads multiplied by the Stencil thickness. Table 1 shows detail description of the component size, pad orientation/dimension and area ratio used in this analysis. As it can be seen from figure 1, this study was restricted to the components on the board that were located in one corner of the board.

The original experiment had accepted the Certificate of Authentication (COA)[6] of the stencil supplier as an acceptable method of stencil qualification. Thus the stencil openings and dimensions are presumed to be in the same order as defined in the supplier qualification.

Table 1- Pad sizes included in the analysis

Pad Name	Orientations	Dimension (mm)	Area Ratio
0805	90	1.29x1.493x.0762	4.530
0603	90	1.067x1.067x.0762	3.500
LQFP 168	-	0.1727x1.59x.0762	1.022
PLCC 28	-	0.601x2.179x.0762	3.090
LQFP 120	-	0.251x1.59x.0762	1.424
BGA 225	-	0.6096X.0762	0.320
0201-10X15	90	0.254x0.381x0.0762	1.000
0201-10X15	0	0.381x0.254x0.0762	1.000
0201-10X14	90	0.254x0.355x0.0762	0.972
0201-10X14	0	0.355x0.254x0.0762	0.972
0201-15X12	90	0.305x0.381x0.0762	0.909
0201-15X12	0	0.381x0.305x0.0762	0.909

Table 2-P/T Ratios

Component	P/T Ratio
01005	20.9%
0201	8.40%
0603	4.30%
0805	3.20%
BGA6	5.80%
BGA225	3.40%
PLCC 28	3.10%
LQFP120	5.40%
LQFP168	6.20%

Gage R&R

Agilent SP50 solder paste inspection system was used for paste transfer efficiency for this study. The P/T (Precision to Tolerance) ratio for various components is shown in Table 2. The P/T ratio was calculated with USL of 150% and a LSL of 50% [4]. As it can be seen from Table 2, all the components except 01005 shows a P/T<10%. This result tells us the Agilent SP50 is highly repeatable. Even though the 01005 component shows P/T>10%, it is still under 30 % and considered to be acceptable.

Design of Experiment

The original experiment was conducted with six factors at two levels. A total of sixteen runs were performed with four boards in each run. The runs that will be used for the current broadband analysis are the first four runs. The first four runs consist of the same setting of stencil type and paste type, i.e., Type 4 paste and 3 mil stencils; however they have variation in process parameters.

Table 3-DOE Factor Levels

Factor	Parameter	Levels		Comment
		(-)	(+)	
PT	Paste Type	Type 3	Type 4	2 vendors
ST	Stencil Thickness	3 mil	4 mil	Laser cut-Electro polished
PS	Print Speed	1.5	3	inches per second
PP	Print Pressure	10	15	psi
SS	Separation Speed	0.05	0.1	inches per second
WM	Wipe Method	With Solvent	Without Solvent	-

Table 4-Selected Runs for Study

Quantity of Boards	Run Order	Paste Type (PT)	Stencil Thickness (ST)	Print Speed (PS)	Print Pressure (PP)	Separation Speed (SS)	Wipe Method (WM)
4	1	1	-1	-1	-1	-1	1
4	2	1	-1	1	1	-1	-1
4	3	1	-1	1	-1	1	1
4	4	1	-1	-1	1	1	-1

Data Analysis and Inferences

The process data uses a total of four board data for each run order to base its conclusions. The process ideally is expected to be centered at 100% of the theoretical volumes and any acceptable tolerances used for process capability calculation were at 40% of either end of the center (USL=140% and LSL=60%). The system tries to understand the defect count of each component on every run and tries to rationalize the best run by providing best possible trade-off over all the components performance. Also the process capability has been seen with a point of view where being in either end of spectrum could be disadvantageous either resulting in too low a paste transfer or too high a paste transfer.

Table 5-Results from Run 1

Orientation	Component	Below LSL(PPM)	Above USL(PPM)	Mean (%)	Std.Deviation (%)	Cp	Cpk	Cpm	Cpl	Cpu
	0805	15.28	0.00	96.36	3.92	1.69	1.39	1.24	1.39	2.00
	0603	0	2080.63	119.39	7.18	1.85	0.95	0.64	2.75	0.95
	LQFP 168	455.22	34177.98	111.62	15.56	0.85	0.60	0.68	1.10	0.60
	PLCC	4.86	309814.72	131.92	16.26	0.82	0.16	0.37	1.47	0.16
	LQFP 120	0	104508.09	128.07	9.48	1.40	0.41	0.45	2.39	0.41
	BGA 225	0	14343.12	124.99	6.85	1.94	0.72	0.51	3.15	0.72
0	201-10x15	4473.49	1287.73	97.15	14.21	0.93	0.87	0.92	0.74	1.00
90	201-10x15	12742.19	11424.90	99.62	17.73	0.75	0.74	0.75	0.74	0.75
0	201-10x14	81.78	820.10	103.58	11.56	1.15	1.05	1.10	1.25	1.05
90	201-10x14	5287.50	8067.28	101.21	16.12	0.82	0.80	0.82	0.85	0.80
0	201-15x12	96.90	125.08	100.35	10.82	1.23	1.22	1.23	1.24	1.22
90	201-15x12	428.93	551.91	100.42	12.12	1.09	1.08	1.09	1.11	1.08

Run 1-Analysis and Discussion

The analysis of Run 1 clearly shows that slow speed run with a low print pressure and without solvent (1.5 inch/s, 10 psi) is causing the defects to occur towards the higher end of the spectrum, i.e., a majority of the components overshoot the USL. The parameters are good in terms of process capability though there is a shift towards the upper limits of the system. The 0201 components have shown average performance in this run with a majority of the pads having excess solder paste transfer. The result is crucial since this is the second most critical component (a critical component could be defined as the one that gets affected rapidly in terms of paste transfer to pads even on slightest change in process-thus we always establish process to suffice these components and work towards components that could have minimal paste transfer variations, like 0805) in terms of size in this assembly. However, the larger components such as 0603, LQFP and BGA have performed with little to zero defects on the lower realm and a low process capability. Another finding is that no components have below a 60% Transfer Efficiency) which gives the understanding that electrical contact or mechanical performance may not suffer from lack of paste.

Table 6-Results from Run 2

Orientation	Component	Below LSL(PPM)	Above USL(PPM)	Mean (%)	Std.Deviation (%)	Cp	Cpk	Cpm	Cpl	Cpu
	0805	0.03	38.44	106.22	8.54	1.56	1.31	1.26	1.80	1.31
	0603	0	201.58	113.15	7.58	1.75	1.17	0.87	2.33	1.17
	LQFP 168	8639.26	68075.33	109.20	20.66	0.64	0.49	0.58	0.79	0.49
	PLCC	31.32	52158.34	116.9	14.21	0.93	0.54	0.60	1.33	0.54
	LQFP 120	0	52857.79	124.28	9.71	1.37	0.53	0.51	2.20	0.53
	BGA 225	0.00	11086.43	117.13	9.99	1.33	0.76	0.67	1.90	0.76
0	201-10x15	47239.31	0.01	78.62	11.13	1.19	0.55	0.55	0.55	1.83
90	201-10x15	19442.89	0.09	82.68	10.98	1.21	0.68	0.65	0.68	1.73
0	201-10x14	433.68	0.13	91.46	9.44	1.41	1.11	1.04	1.11	1.71
90	201-10x14	818.84	0.18	90.61	9.72	1.37	1.05	0.98	1.05	1.69
0	201-15x12	3060.51	0.00	84.70	9.02	1.48	0.91	0.75	0.91	2.04
90	201-15x12	376.24	0.00	88.88	8.51	1.55	1.12	0.95	1.12	1.98

Run 2-Analysis and Discussion

The analysis of Run 2 which has the highest speed and a high pressure (3 inch/s and 15 psi) has the worst performance of all the runs. The entire process has very low C_{pk} values that are likely caused by either too low a paste transfer on certain components or too high a paste transfer on certain other components. It clearly shows that process lacks the capability to print 0201 components with minimal paste transfer. It has to be understood that the upper process capability (Cpu) values look extremely good and would be a gross misunderstanding if used to judge the process. The absolute count of defects in Run 2 is less than in Run 1, however, the 0201 components across all pad locations have poor paste transfer, possibly leading to failures if this process is used for printing the board.

Table 7-Results from Run 3

Orientation	Component	Below LSL(PPM)	Above USL(PPM)	Mean (%)	Std.Deviation (%)	Cp	Cpk	Cpm	Cpl	Cpu
	0805	0.32	738.79	108.80	9.81	1.35	1.06	1.01	1.65	1.06
	0603	0	349.68	116.55	6.91	1.92	1.13	0.74	2.72	1.13
	LQFP 168	33.05	49.32	100.48	10.14	1.31	1.29	1.31	1.33	1.29
	PLCC	15.39	131349.7	123.05	15.12	0.88	0.37	0.48	1.38	0.37
	LQFP 120	0.56	5.67	120.37	12.4	1.07	0.52	0.55	1.62	0.52
	BGA 225	0	681.75	119.38	6.43	2.07	1.06	0.65	3.07	1.06
0	201-10x15	7282.81	63.061	91.13	12.74	1.04	0.81	0.85	0.81	1.27
90	201-10x15	13834.02	1684.11	94.31	15.58	0.85	0.73	0.80	0.73	0.97
0	201-10x14	73.3	5.13	97.00	9.74	1.36	1.26	1.30	1.26	1.47
90	201-10x14	1422.80	15.26	93.37	11.18	1.19	0.99	1.02	0.99	1.39
0	201-15x12	44.49	0.02	93.46	8.53	1.56	1.30	1.24	1.30	1.81
90	201-15x12	16.18	0.19	96.01	8.66	1.53	1.38	1.39	1.38	1.69

Run 3-Analysis and Discussion

The third run was of significant interest since it provided the best recommended settings for the earlier 01005 experiment[4]. This run (set of settings) also provides the highest print speed and separation speed of all the runs (thus not trading off on any aspect of throughput). It also has a cost saving in aspect of not requiring a solvent wipe. The process in this scenario also has the best performance with regards to 0201 process capability (irrespective of orientation of pads) among all the runs. The process unfortunately has some of the worst performances in terms of process capability for larger pads such as PLCC, LQFP and BGA. However, this run has the lowest PPM value (cumulative of all components) among all the runs. The component failures and performance is an extremely difficult question to answer. But it is generally agreed that a process where no component (smallest to biggest) fails mechanically or electrically or does not have a pattern of poor performance should be deemed acceptable and recommended as the stable process.

Table 8-Results from Run 4

Orientation	Component	Below LSL(PPM)	Above USL(PPM)	Mean (%)	Std.Deviation (%)	Cp	Cpk	Cpm	Cpl	Cpu
	805	1.39	159.14	105.24	9.65	1.38	1.2	1.21	1.56	1.2
	603	0	0	118.40	8.54	1.56	0.84	0.65	2.27	0.84
	LQFP 168	42.45	3132.76	107.18	12.00	1.11	0.91	0.95	1.31	0.91
	PLCC	38.63	115237.73	121.37	15.53	0.85	0.4	0.50	1.318	0.4
	LQFP 120	0	91881.45	127.519	9.38	1.42	0.44	0.45	2.39	0.44
	BGA 225	0	24515.94	121.83	9.23	1.44	0.65	0.56	2.23	0.65
0	201-10x15	6043.05	0.03	85.46	10.14	1.31	0.83	0.75	0.83	1.79
90	201-10x15	5128.68	1.53	88.39	11.05	1.20	0.85	0.83	0.85	1.55
0	201-10x14	65.68	171.68	101.31	10.80	1.23	1.19	1.22	1.27	1.19
90	201-10x14	32.63	7.19	98.34	9.60	1.38	1.33	1.36	1.33	1.44
0	201-15x12	42.48	0.00	91.65	8.05	1.65	1.31	1.15	1.31	2
90	201-15x12	5.93	0.14	96.84	8.41	1.58	1.46	1.48	1.46	1.71

Run 4-Analysis and Discussion

This run has the lowest print speed and highest print pressure among all the runs in the process. The performance of the 0201 Components is the second best among all the runs in this experiment. The defects in terms of PPM are higher as compared to that of Run 3. As in Run 3, Run 4 also has undesirable performance with respect to the larger pads. The process is comparable to Run 3 in nearly all terms of performance (except for 0201 components). It has to be however understood that a Very high pressure applied on the stencil might seriously affect its long time performance or number of boards for which it can be used to print.

Table 9-Results from all Runs-Cumulative All Components

Run	Below LSL(PPM)	Above USL(PPM)	Mean (%)	Std.Deviation (%)	Cp	Cpk	Cpm	Cpl	Cpu
1	2358.51	48720.16	131.47	14.188	1.45	1.00	0.98	1.82	1.08
2	8004.00	18441.83	120.38	12.95	1.58	1.02	0.94	1.58	1.58
3	2272.29	13494.28	125.39	12.73	1.61	1.19	1.13	1.83	1.40
4	1139.99	23510.76	126.35	12.24	1.61	1.14	1.11	1.81	1.41

Cumulative of Runs-Discussion

The cumulative process capability table (Table 9) clearly shows that Run 3 has the best overall C_p and C_{pk} values among all the runs. However, when we look at this table we see that mean transfer efficiency when looked at on a cumulative way (for all components across all boards in that run) does not allow one to discern the best run. The mean transfer efficiency values looks to be in the same "Ball Park". However, the cumulative process capability index values show that Run 1 and Run 2 are of lower values (3 sigma) as compared to that of Run 3 and Run 4 (3.5 sigma). Table 10 shows the yield significance.

Table 10- Sigma chart

Sigma	Defects	Yield	C_{pk}
3	66,800	93.32%	1
3.5	22,700	97.73%	1.17

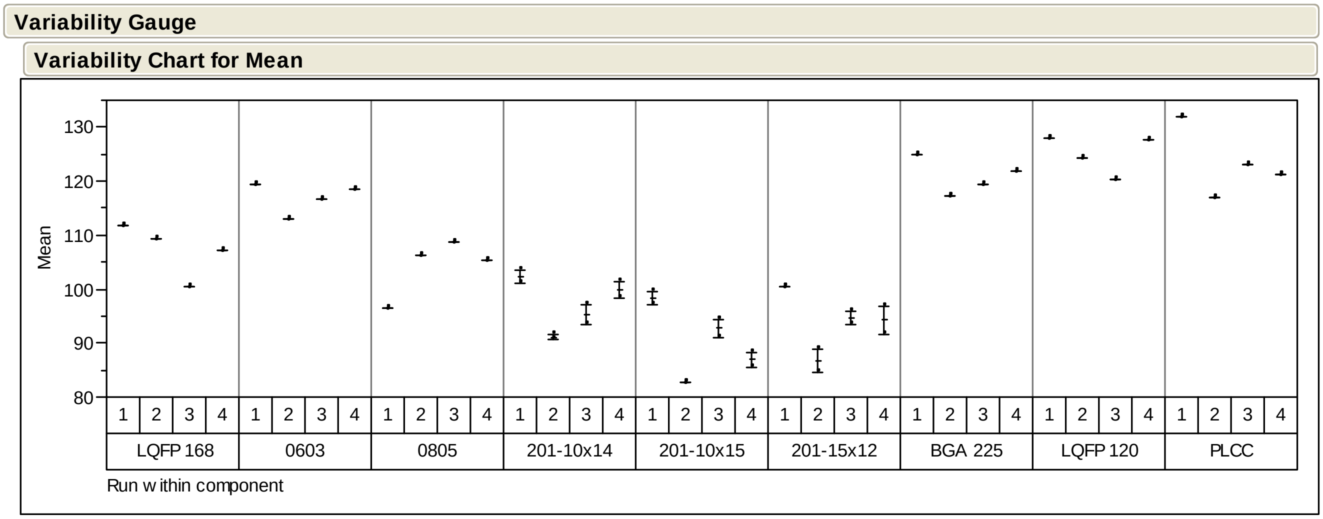

Figure 2. Results for All Components-Cumulative of all Runs

The performance across various components in all runs clearly shows that the leaded packages seem to have higher transfer efficiency as compared to passives. The 0201 passives performance also clearly shows that the overall transfer efficiency is always close to the aperture opening or less also across all runs. Thus, defects that can be induced by excessive paste (like bridging, shorts, etc.) do not occur for the smallest passives.

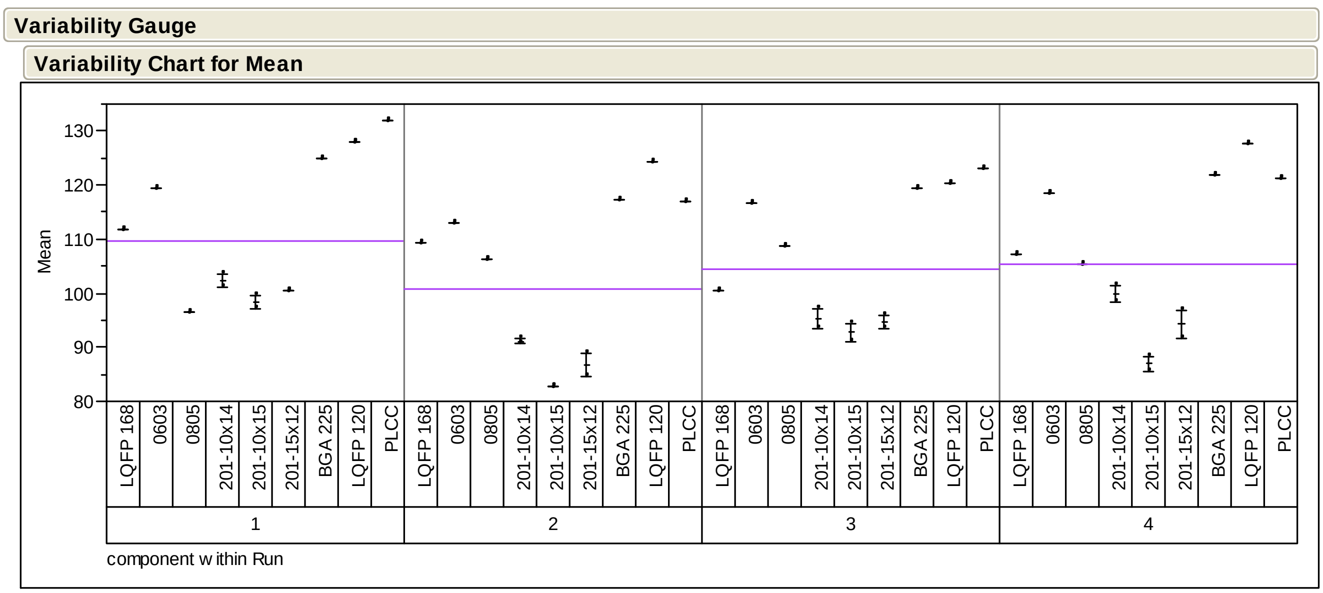

Figure 3. Results from all Runs-Cumulative All Components

The performance of the components within the run clearly shows that excessive paste transfers are always induced by the larger components. The leaded packages such as LQFP and PLCC have poor performance across all the runs and settings in this study.

Mechanical testing of Components

The components were tested for mechanical strength by the standard shear testing process. The shear testing results were compared to some of the literature[7] results for various components printed with lead free paste. The greatest challenge to this analysis is the non availability of results from shear tests for various smaller components (0201).

The experiments were run with different test loads since there were components with a 400 g test load requirement to ones with close to 10 kg requirements. A summary of the test load used for the larger components and smaller components are provided in Table 11. The failures mainly occurred at the interface between component and solder i.e. in many of the cases the solder was mostly left on the board.

Twenty components were sheared off following standard operating procedure for DAGE 4000. The components were sheared always across the component to provide maximum leverage or opportunity for the component to resist the shearing. Shear test result for Run 3 is presented in Table 12.

Table 11-Test Setup-DAGE 4000

Parameter settings	Range
Test speed	8 mil/sec
Test Load	.5 kg
Land Speed	20 mil/sec
Range	10 kg /400 g /5 kg
Over Travel	12 mil/6 mil

Table 12 –Shear Test Results

Pad Name	Orientations	Shearing Force (Grams)	Area Ratio
0805	90	6100	4.530
0603	90	3140	3.500
0201-10X15	90	510	1.000
0201-10X15	0	478	1.000
0201-10X14	90	480	0.972
0201-10X14	0	425	0.972
0201-15X12	90	552	0.909
0201-15X12	0	493	0.909

Conclusions

The shear test result indicates that larger component such as 0805 and 0603 give bond strength comparable to data reported by NIST solder paste data base[8] and other researchers[7, 9]. This result is very encouraging since it indicates that one stencil thickness may be adequate enough to deliver paste necessary to provide enough mechanical strength to hold the larger components in place. Clearly additional experiment and analysis is required to fully understand and confirm this conclusion.

In regards to the printing requirements, the best run among all the runs was found to be 3 inches /second squeegee speed with 10 psi pressure. This run was the best setting for the 01005 experiments [4] as reported in the literature. Thus, if the pad matrix in the study has a very high number of larger pads as compared to 01005 or 0201 components it may be advisable to consider settings such as those described in Run 3. The real decision driver in a "Broadband Printing" process is the process itself. The study from overall performance across various runs clearly show that the larger components have had a paste transfer of 100% or over whereas the smaller components have had a paste transfer of below 100% .This may be desirable since it has the potential for satisfying both large and small component paste requirement.

Future Work

This analysis is the "tip of the iceberg" in respect to understanding the requirements for mixed component board. Additional work is necessary to fully understand the electrical and mechanical requirements of both small and large component through broadband printing and other printing methods. Stay tuned!

Acknowledgement

The authors would like to thank Mr. Sudeep Nambiar whose masters thesis provided a basis and motivation for this work.The authors would also like to thank the Integrated Electronics Engineering Center (IEEC) at Binghamton University for their support towards the research.

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