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Nano Technology Improve Critical Printing Process

Omar García, Enrique Avelar, Manuel Domínguez, Francisco Barajas, Jaime Medina,
Dason Cheung, Juan Coronado, Zhen (Jane) Feng, Murad Kurwa.

FLEXTRONICS International Inc.
Carretera Base Aérea 5850 Col. La Mora; Zapopan, Jal, 45100, México.

Abstract
The challenges of successful solder printing in the High Volume / Low Mix cell phone environment, which is linked with the continuing trend to miniaturize electronic assemblies, requires a new approach to improve the printing capabilities and process repeatability. Actual stencil technologies such as electroform or laser-cut limit the stencil opening due to aspect and area ratios at the smallest devices producing a very tight process window. It's here that Nano Technology will assist in the printing process. Using Nano Coating over the stencil openings to smooth the surface and improving the paste release, helps reducing aperture openings, and creates a wider process window. Additionally, panel stretch and PCB fabrication tolerances produce a silent non constant variable that moves the process outside the quality printing window, without obvious signs of variation.

To obtain an advantage, and successfully implement this technology, the process requires new controls of chemical and parameter settings. We will discuss some aspects of process optimization and how this very tight process window is affected, by identifying the challenging process parameters, including circuit board fabrication, component pad design, and printing parameters (speed, separation, pressure, etc.). This printing study will consider the effects of print speed, print pressure, and separation speed, to optimize solder paste transfer efficiency (TE) to establish an statistical process control that gives real time warnings of an out of control printing process. We will discuss our data results which will include the advantage of using Nano stencil vs. E-Fab and Laser NiEX. TE improvement is 5% at the smallest stencil aperture across a panel of 4 images. The cleaning speed significantly reduces defects from 2% with a 50mm/sec, to zero defects using 20mm/sec. By improving the TE by 5% will increase the number of prints without a paste bridge on any board, even up to10 prints between cleaning.

Key Words: AR: area ratio; Nano technology; miniature components; Stencil; TE (Transfer Efficiency); SPC (Statistical Process Control); IPA (Isopropyl Alcohol); HVLM (High Volume Low Mix); C& E (Cause & effect analysis); UCL (Upper control limit); LCL (Lower control limits); CSP (Chip scale package); SPI (inline automatic solder paste inspection); DPPM (Defect Part Per Million); SOP (Standard operation procedure); X (Critical variable); X (Controllable); PCB (Printed circuit board); UPH (units per hour); W:Wet; V: Vacuum; D: Dry; OSP (Organic solderability preservative); SEM (Scan Electron Microscope).

Introduction

Printing process due miniaturization of the cell phones and other portable technologies has become a difficult process to control. Restriction of pad size, pad type, stencil aspect & area ratio´s with the combination of PCB fabrication tolerance & stretches affect in greater manner the paste deposit shape and process repeatability. As today it has become extremely difficult to get the printing in control due to the tight cycle time requirements that need to keep up with the production rates of the ultra high volumes lines. These variables affect the gasketing, pushing the process to have a cleaning cycle after every printout in most of the cases, leaving no space for adjustment that increases process stability. The analyses made on this paper were made to improve the printing performance consider the machine adjustments & the stencil type separately. The steps followed to get better consistency & process repeatability were:

1. Screen Printer characterization.
2. Stencil technology selection.
3. Impact of cleaning settings.
4. Transfer Efficiency (TE) analysis.
5. Cleaning settings vs. Printing settings.
6. Stencil opening interaction.

Some variables were considered as noise such us material tolerances, paste and paper quality and consistency. Other variables that affect the prints have been frozen as much as we could such us humidity & temperature. First step was to characterize the screen printer to see variables weight and importance.

Screen Printer characterization:

The stencil technology and stencil design was analyzed subsequently due to was considered as very important. The screen printer was split in 8 sub systems; critical variables and the interaction between those per each sub system were verified. Main goal is to reduce noise and have it under control for the follow on experiments. The sub-systems reviewed were: transportation & rail system, table & board holder system, stencil clamping system, alignment system (screen and camera systems module), printing system, stencil cleaning system, environmental system and software control system.

Operation map detail:

Printing process was followed step by step with the interaction of each sub-system to identify each variable and the importance of each and one of those. Variables were identified and selected in 4 categories: 1) "SOP" (Standard operation procedure) defined by an instruction or manual, 2) "X" Critical Variable; 3) "C" (controllable), variable that can be adjusted by user & 4) Noise; things that the user are not able to control or not considered in this study. Figure.1, 2 & 3 showed step by step the printing process & variables.

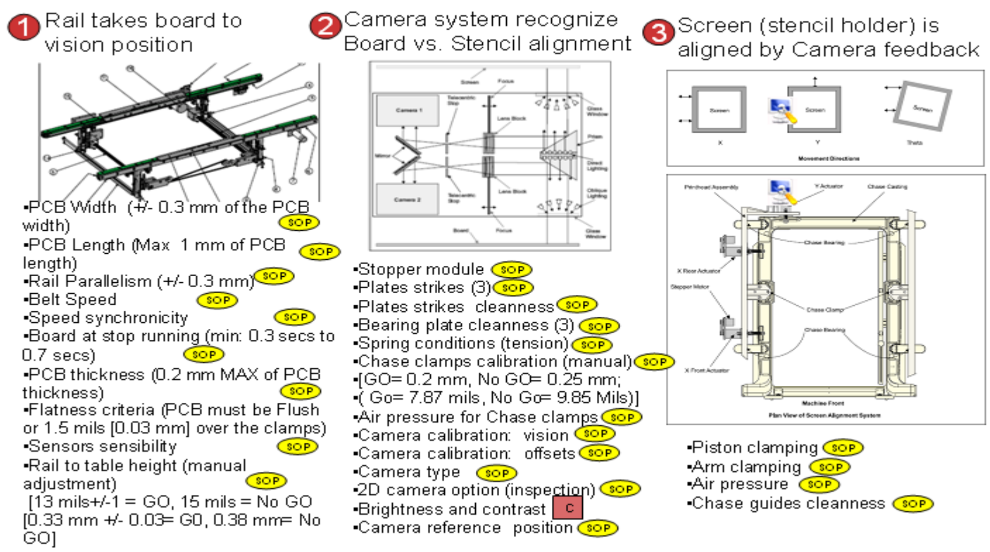


Figure 1: 1st 2nd & 3thd step of the printing process.

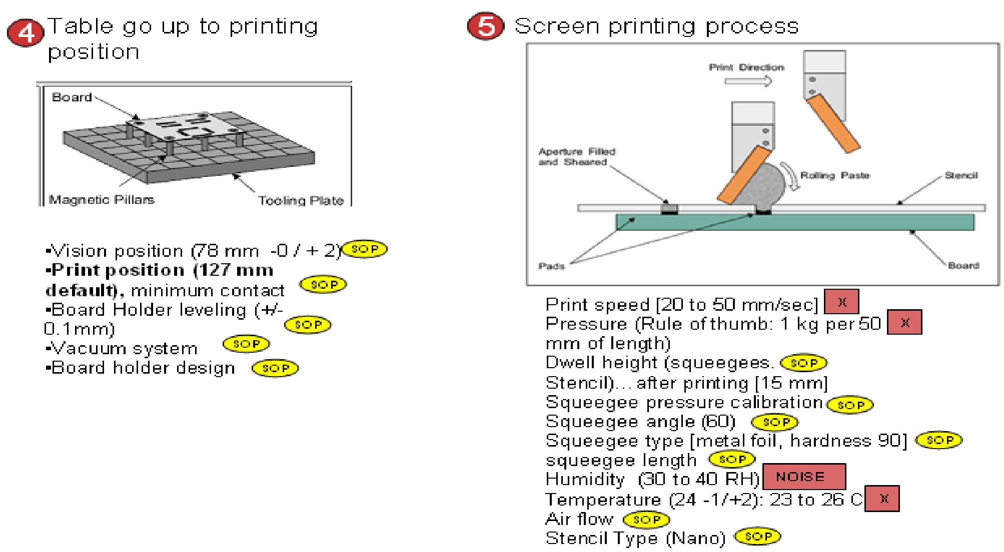


Figure2: 4th & 5th step of the printing process.

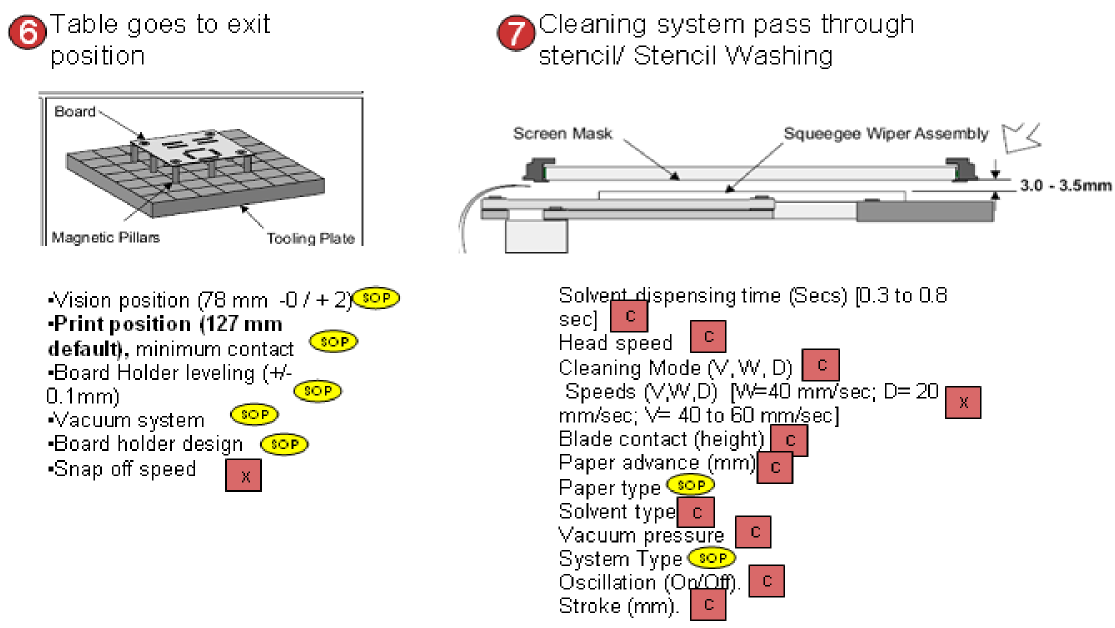


Figure 3: 6th & 7th step of the printing process with the category for each variable.

The analysis produced a Cause & Effect analysis (C&E) table (see table 1), where critical variables (X), controllable variables (C), standard operation procedures (SOP), and trivial / noise variables can be appreciate.

Table 1: C&E Printing process main variables.

Sub system	Variable	Score	Type
Rail system	Rail to table height (manual adjustment) [13 mils+/-1 = GO, 15 mils = No GO [0.33 mm +/- 0.03= G0, 0.38 mm= No GO]	369	SOP
Screen cleaner	Cleaning Mode (V, W, D)	324	X
Screen cleaner	Speeds (V,W,D) [W=40 mm/sec; D= 20 mm/sec; V= 40 to 60 mm/sec]	324	X
Rising Table	Board holder design	309	X
Rising Table	Print Height Calibration (Print position: 127 mm default), minimum contact	297	SOP
Rail system	Clamp type: :Board clamp	288	SOP
Rail system	PCB thickness (0.2 mm MAX of PCB thickness)	288	SOP
Rail system	Flatness criteria (PCB must be flush or 1.5 mils [0.03 mm] over the clamp).	288	SOP
Environment System	Temperature (24 -1/+2): 23 to 26 C	288	SOP
Environment System	Diffuser / Chamber (air Flow)	288	SOP
Environment System	TCU type	288	SOP
Print Carriage	Pressure (Rule of thumb: 1 kg per 50 mm of length)	279	X
Print Carriage	Squeegee pressure calibration	279	X
Print Carriage	Squeegee angle (60)	279	SOP
Screen cleaner	Blade contact (height)	270	X
Screen cleaner	System Type Vortex	270	SOP
Rising Table	Board Holder Leveling (+/- 0.1 mm)	249	X
Screen cleaner	Vacuum pressure	240	SOP
Print Carriage	Print speed [20 to 50 mm/sec]	231	X
Screen cleaner	Solvent dispensing time (Seconds) [0.3 to 0.8 sec]	192	C
Screen cleaner	Solvent type	192	X

Based on these findings, the printer was adjusted to reduce print to print variability. As mentioned before the stencil was not considered in the C&E analysis due a more extensive analysis following this stage. The printer calibration & adjustments process was made before every experiment.

Next step was to analyze the stencil technology and design, as today common stencil type used are laser, Nickel laser cut & E-Fab´s (electro-form). One of the latest developments, the novel laser cut with a Nano coated come up as a good opportunity to improve the printing process, so this raise the need to explain to some extent the Nano coated stencil fabrication process steps by step (that may change from others stencil houses).

Nano coated process:

Stencil used in the study follow the next steps after laser cutting process:

- Alcohol degreasing.
- Brushing process with water on squeegee and printed circuit board side.
- Cleaning step with de-mineralized water.

After that, follow the step of Figure. 4:

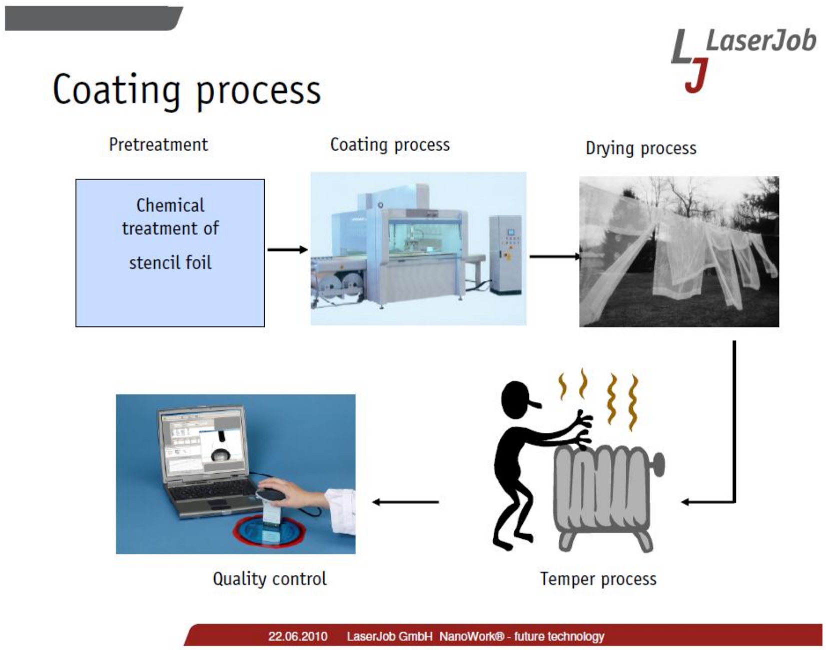


Figure.4: Explanation of the Nano coated process.

Other variables that affect the stencil fabrication & printing process that you need to taking in a count beside the stencil house are the laser technology, speed of cut, foil material, foil thickness/flatness, cutting parameter, chemical control, tension, with or without electro-polishing, laser machine calibration & maintenance frequency.

Stencil technology selection:

Compare the different stencil technologies available in the market was the second step to improve printing performance into our ultra HVLM production lines. The stencil technologies selected were a Laser cut with Nano coating (Nano), E-Fab (NiEX), and a Laser cut over a Nickel foil (Nickel). The analysis used panels from a mobile mass product line (4 X PCB panels) and from different lots (Figure. 5 gives an idea of the mobile phone and CSP location). The components reviewed was a 0.4 mm pitch CSP´s (16 mils), that is the one with the highest print challenges (with 81 solder balls shown at Figure 6). The PCB land pattern has round shape pads of 0.2413 mm (9.5 mils) in diameter with OSP plating. The Nickel stencil use an opening of 0.2413 mm (9.5 mils) due to release issues, see Figure 7, and the Nano coated and E-Fab (NiEX) use an smaller opening of 0.2184 mm (8.6 mils) that is shown on Figure 8; All stencils have 0.1016 mm (4 mils) in thickness, stencil design follows same square type with round corners. (See table 2).

Table 2: Stencil technologies & Apertures

Stencil technology	Stencil opening : square with round corners
Laser cut with Nickel foil	0.2413 mm (9.5 mils)
Laser cut with a Nano coating	0.2184 mm (8.6 mils)
E-Fab (NiEX)	0.2184 mm (8.6 mils)
Stencil thickness:	0.1016 mm (4 mils)
Squeegee size: Angle:	300 mm 60º
Paste type:	Power size: Type 3 No clean Lead free SAC 305 ROL0

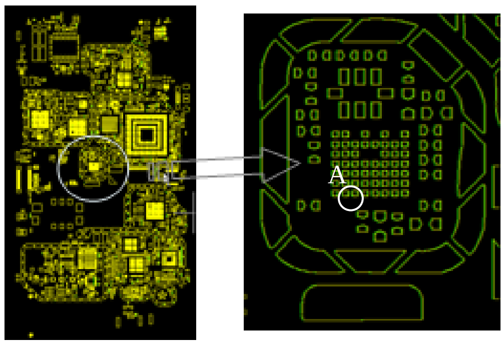


Figure 5: Single images of a mobile PCB panel (4X), CSP of 0.4 mm pitch CSP's on the right side.

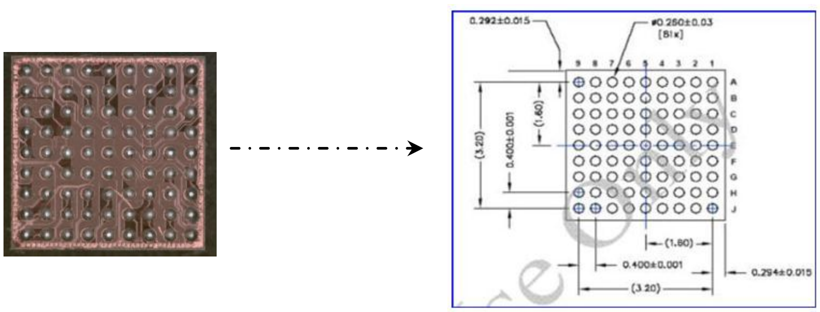


Figure 6: Bottom side of one of the CSP analyze with pitch on 0.4 mm, CSP solder ball of 0.26 +/-0.03 mm

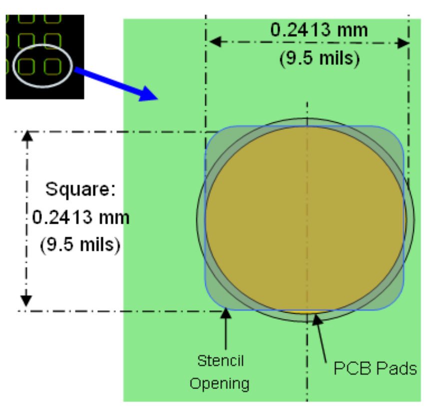


Figure 7: Close up of stencil opening design for Nickel laser cut.

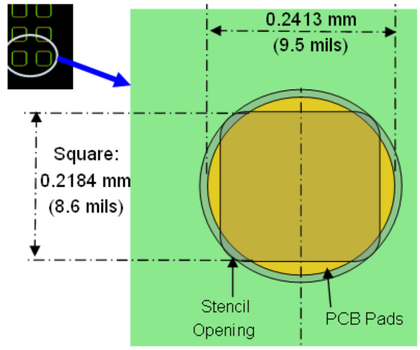


Figure 8: Close up of stencil opening design for Nano & E-Fab.

The steps to evaluate the stencils were using a screen printer from production line; before start the machine get a mechanical parts verified and calibration. Critical variables follow the C&E analysis adjustments as the best known settings so far. After 1 hour of production (rate: 240 UPH) the stencil was change, cleaning frequency was every print. All data was recollected by inline automatic SPI equipment. The chemical used was IPA (alcohol) with standard cleaning paper. The printer use a cleaning system called “cyclone” (used in all the experiments). All data analyzed was taken from the 0.4 mm pitch CSP´s (for this stage: 81 balls per components, 1 component per PCB, 4 PCB´s per panel). As shown on Figure 9, the Nano coated stencil shown a less dispersion and better performance. Note: Panel stretch affect the 3stencils in similar manner due no screening was made before the run.

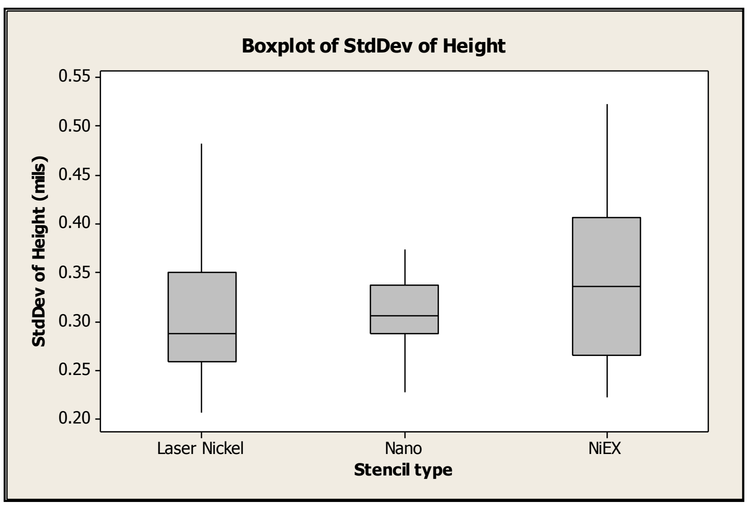


Figure 9: Box plot of paste height: 3 stencil technologies performance from 720 PCA´s of 3 hours of regular production boards (data in mils).

A more stable process was reach using the Nano coated stencil; figure10 shows the standard deviation of heights among panels (sample Mean) and between each pad (Sample Range). The lower range means a more uniform printing among all pads.

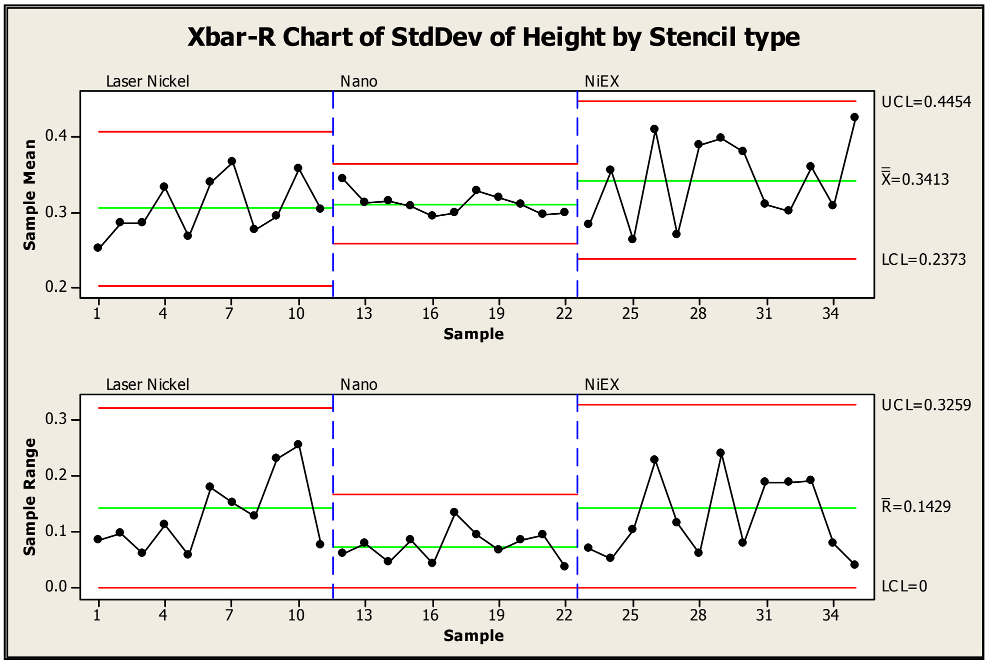


Figure10: Xbar R chart for Std. Dev. of height in mils (lot size: 720 units per stencil type).

Graph of figure 11 show paste behavior per images of the panel. The panel stretch and PCB manufacturing tolerance must be considered as noise in these replicates due to panels come from mass production. The stencil/PCB pad gasketing was more affected at the Laser Nickel & E-Fab (NiEX), showing the Nano a more uniformity across the panel with less dispersion. Note: cleaning was made every print.

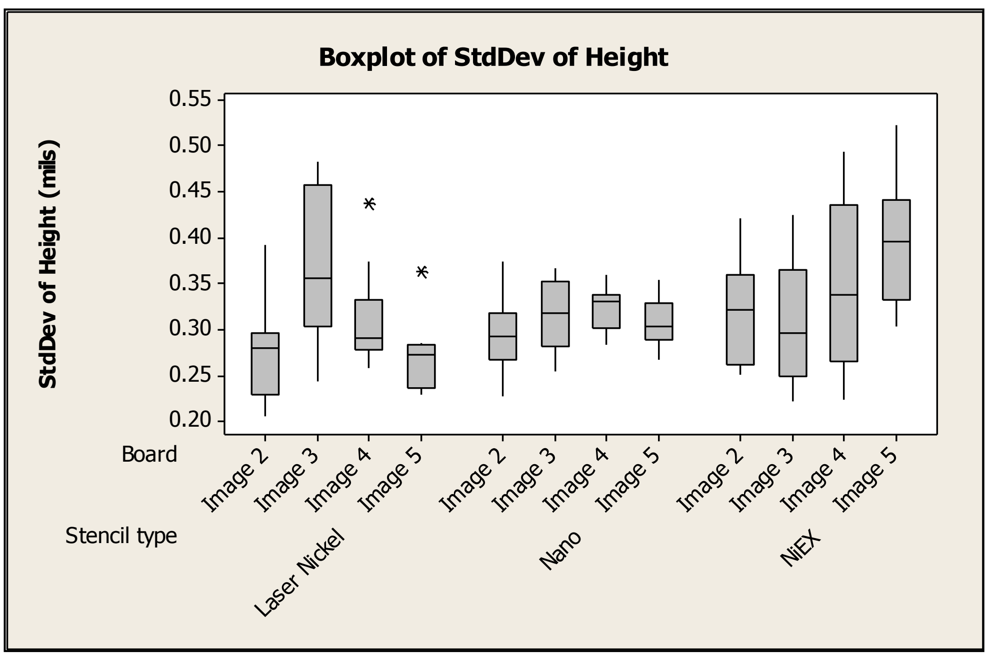


Figure11: Box of paste height per PCA image and Stencil technology (lot size: 720 PCA´s, 240 per stencil type).

Figure 12 illustrates the test for equal variance for the 3 stencils where a low P value was obtained; which demonstrated that the Nano stencil is indeed different by having a better printing performance with less variation with regards to paste volume.

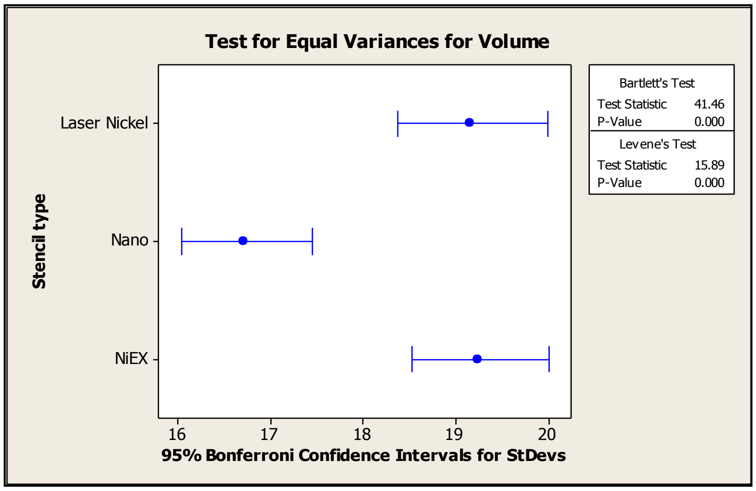


Figure 12: Stencil technologies Test for equal variance comparison. (Lot size: 720 units).

A 2D contour plot graphical image of the paste heights for the CSP (with 81 pads) is showed on Figures 13, 14 & 15, where showed a Nano stencil with more uniform paste height across the device (CSP of 0.4 mm pitch).

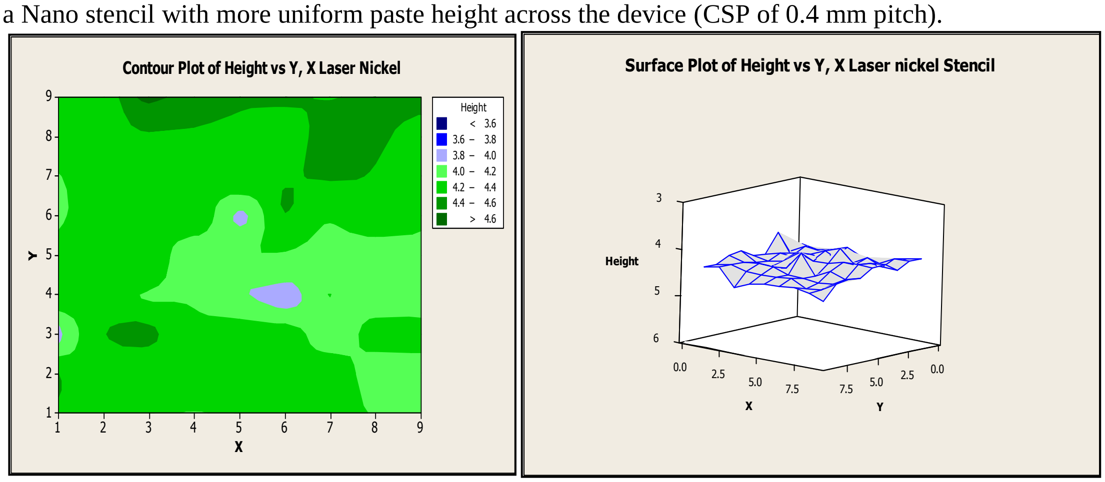


Figure 13: Laser Nickel stencil: paste height distribution along the 0.4 mm pitch CSP (in mils). Lot size: 240 PCA

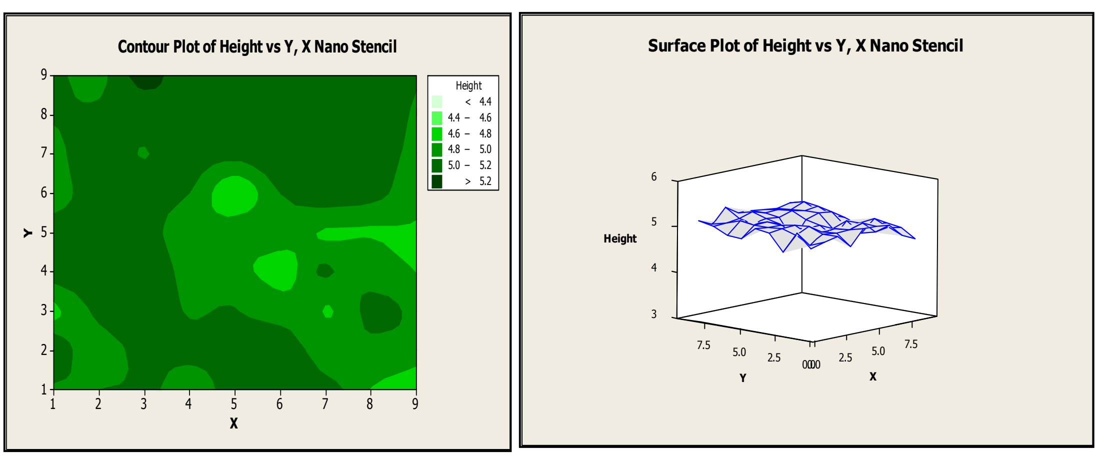


Figure 14: Nano coated stencil, paste height distributions along the 0.4 mm pitch CSP (in mils), lot size: 240 PCA.

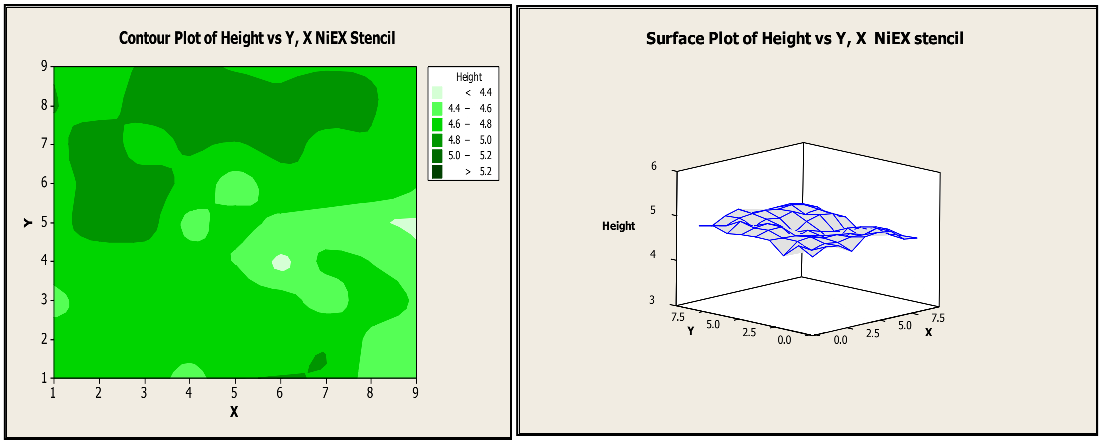


Figure 15: E Fab (NiEX): Paste height distributions along the 0.4 mm pitch CSP (in mils). Lot size: 240 PCA.

Yield on FVT (functional verification test) was capture through time on figure 16 (where the data showed as reference). From beginning to end time the first stencil used was the regular laser cut, followed by the laser cut with Nickel foil, then E Fab and now the latest technology in use it's the Nano coated. All monitored yields follow the failures on the CSP of pitch of 0.4 mm.

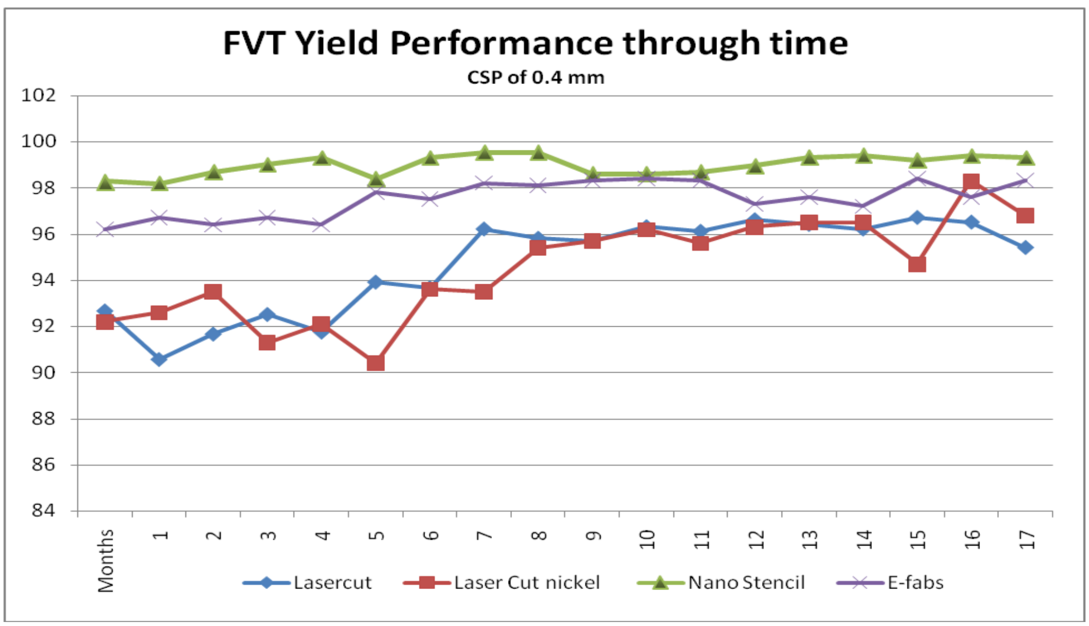


Figure 16: General yield trend on FVT per type of stencil (CSP of 0.4 mm pitch).

Impact of cleaning settings:

The Nano stencil was define as the best based on the previous prints results, to understand the interactions of the cleaning variables with the printing repeatability a new experiment was made to improve and fine-tune the screen printing process. The cleaning system was adjusted in 7 combinations with 3 replicates to find the one with better performance. The cleaning system has several options and 3 basic type of cleaning modes: Wet, Dry & Vacuum. The letter "**W"** stands for a "WET", a cleaning type that uses solvent or a cleaner, which soaked the paper before cleaning the stencil. The letter "**V**" stands for "VACUUM", a cleaning type that move the paper and vacuum is applied at the same time the paper clean the bottom side of the stencil. The letter "**D**" stands for DRY, a cleaning type that uses the paper as it is "dry". The printer cleaning system can take any combination and sequences that you set. As an example when a WVD is establish, means that there are 3 cleaning cycles following one another. Wet cycle is followed by Vacuum cycle and at the end a Dry cycle.

The experiment was set (without activating the printer cleaning system) to see maximum amount of prints without getting a bridge in the panel. Stencil was washed after every replicate. The cleaning settings used are on table 3 and printing variables used are on table 4. Isopropyl alcohol (IPA) and Water base cleaner were also included in the analysis

Table 3: Different cleaning settings used in the experiment.

Variable	Setting A	Settings B	Setting C	Settings D	Settings F	Settings G	Settings H
Paper Type	Std.	Std.	Std.	Std.	Std.	Std.	Std.
Solvent Dispense Time (Seconds)	0.4	0.4	0.4	0.4	1	1	1
Cleaning sequence	**WVD**	**V**	**WV**	**WD**	**WD**	**WD**	**WD**
W=Wet Speed (mm/sec)	30	70	60	60	60	40	40
V= Vacuum speed (mm/sec)	30	35	30	N/A	N/A	N/A	N/A
D= Dry Speed (mm/sec)	30	70	N/A	50	50	20	20
Chemical use	IPA	IPA	IPA	IPA	WATER BASE	WETER BASE	IPA

Table 4: Fixed parameters for this trail

Parameters	Fix Setting
Paste Type	No clean
Power size:	Type 4
Flux type:	ROL 0
Alloy	Lead Free SAC 305
Print speed (mm/sec)	38 mm/sec
Print Pressure(Kg/Cm^2)	6.8
Separation speed (mm/sec)	1
Print Gap (mm)	0
Temperature (ºC)	25
Humidity (% RH)	38.5%
Cleaning system:	Cyclone ("On" for Wet & Dry)
Squeegee size: Angle:	300 mm 60º
Stencil thickness:	0.1 mm (4 mils)

The experiment has 3 replicates for each combination, the run stop until a bridge was obtained in any of the 4 boards of the panel. Stencil was washed after every run, results shown on table 5.

Table 5: Results of the 3 replicates in the consecutive test printing without cleaning

Clean Setting	**# of successful prints without a bridge**									
Replicate # 1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	10
V	**0.337051**	**0.403180**	**0.354942**	**Bridge**						
WD	**0.337399**	**0.333729**	**0.393982**	**Bridge**						
WD (low speed)	**0.372402**	**0.478632**	**0.383051**	**0.449736**	**0.376399**	**0.438238**	**0.364676**	**Bridge**		
WV	**0.401612**	**0.337724**	**0.462055**	**0.350329**	**Bridge**					
WVD	**0.431078**	**0.328412**	**0.449045**	**Bridge**						
Replicate # 2										
V	**0.356445**	**0.334621**	**Bridge**							
WD	**0.332580**	**0.460886**	**0.333824**	**0.419773**	**Bridge**					
WD (low speed)	**0.381413**	**0.373718**	**0.437109**	**0.407273**	**0.405155**	**0.398950**	**0.464727**	**0.431064**	**0.512082**	Bridge
WV	**0.410186**	**0.365831**	**0.425010**	**Bridge**						
WVD	**0.421896**	**0.440061**	**0.353742**	**0.435346**	**0.365549**	**Bridge**				
Replicate # 3										
V	**0.375974**	**0.327737**	**0.402255**	**0.349957**	**Bridge**					
WD	**0.355030**	**0.460989**	**0.344715**	**0.466521**	**0.350124**	**Bridge**				
WD (low speed)	**0.443666**	**0.404449**	**0.458196**	**0.573333**	**0.404234**	**0.489150**	**0.363598**	**0.464529**	**0.42393**	Bridge
WV	**0.453356**	**0.361739**	**0.400837**	**Bridge**						
WVD	**0.398466**	**0.341628**	**Bridge**							
Note:	Data capture its Std. Dev. Of paste height (Lot size: 83 panels).									

Figure 17 shows box plots for volume deposit on the 0.4 mm pitch CSP', the data capture demonstrates that the combination Wet-Dry (WD) using a slow speed performed better with volume amount, from what we can tell so far this is the cleaning mode with better performance. In the WD set there are some differences in speed & cleaner type that are important to understand with more detail.

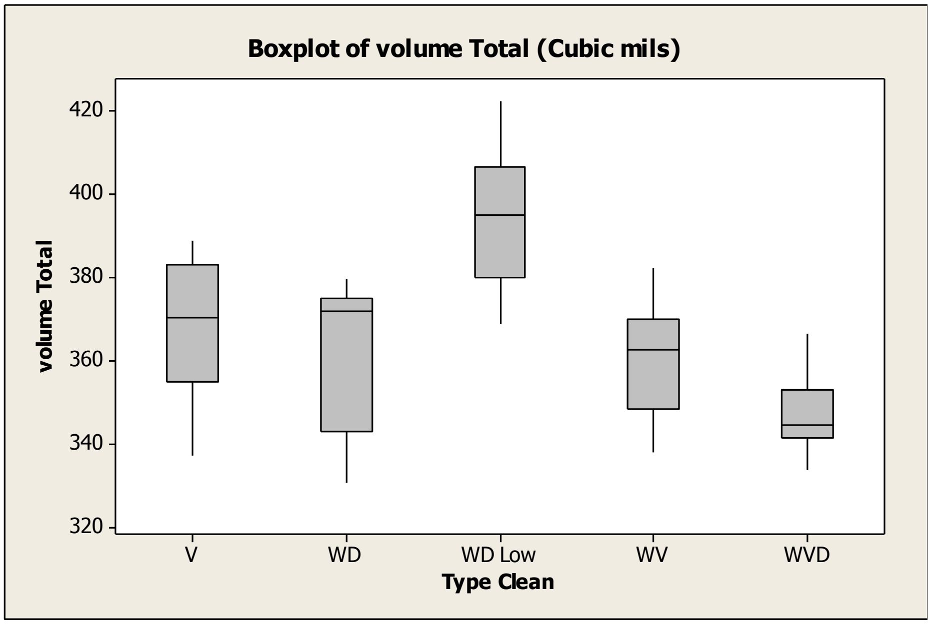


Figure 17: Volume box plot performance per type of cleaning settings (Lot size: 83 panels).

The WD setting with the Nano coated stencil demonstrates a more “stable” deposit along the panel (Figure 18), also point up to higher volume values, the combination of water base cleaner and Wet-Dry with slow speed was the best combination of all (WD Low) for this first set up validation.

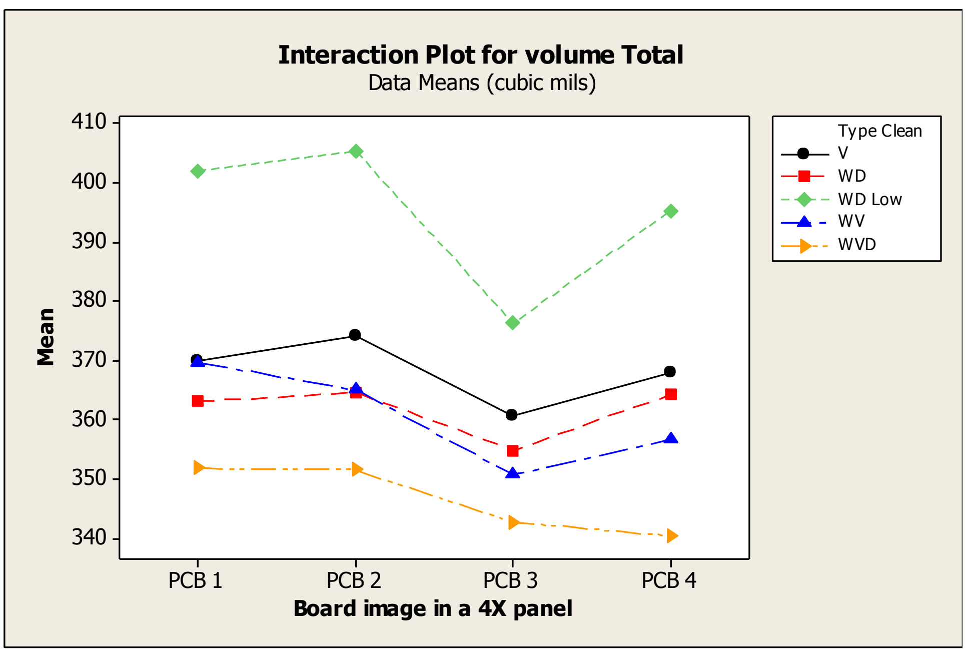


Figure 18: Print performance on “Volume” per images of the panel (Lot size: 83 panels).

An overall paste behavior through prints (using the transfer efficiency [TE]) can be appreciated at figure 19. TE has an increase in every print. Value of TE above a 100% it´s an indicator of paste contamination at the bottom side of the stencil.

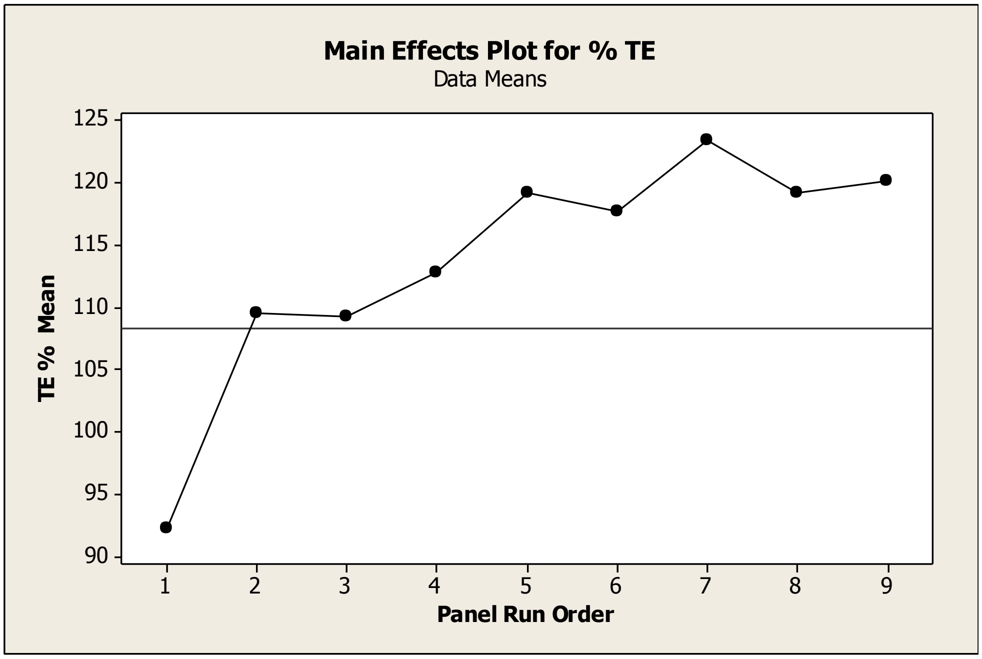


Figure 19: Transfer efficiency (TE) along the different run. (Lot size: 83 panels).

Using the same data a Weibull plot was graph (showed at Fig 20), which indicated "failure percentage prediction" per type of cleaning set used. The common set WVD (Wet-Vacuum-Dry) used shows "defects" even cleaning every board (5%); meanwhile the best prediction "WD" (Wet-Dry) using an speed of 20 mm/sec can print more than 2 panels without cleaning.

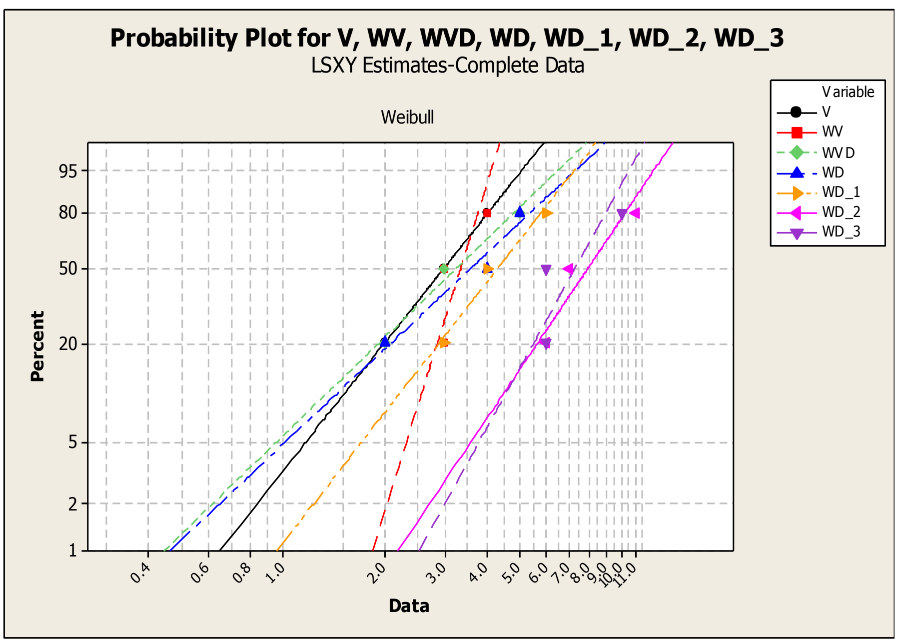


Figure 20: Weibull probability plot per type of cleaning settings: Y axis it's the defect % and X axis represent cleaning frequency. (Lot size: 83 panels).

Cleaning Speed impact:

So far the best combination for cleaning found in the last experiment was the "WD" (Wet-Dry) combination; a prediction of the cleaning speed was calculated using a Weibull plot (Figure 21) with 2 different speeds: 20 mm/sec vs. 50 mm/sec. At speed of 50 mm/sec you will have approximated 2% of defect even cleaning every board. By reducing the cleaning speed to 20 mm/sec the cleaning frequency can move to even 3 prints without defects.

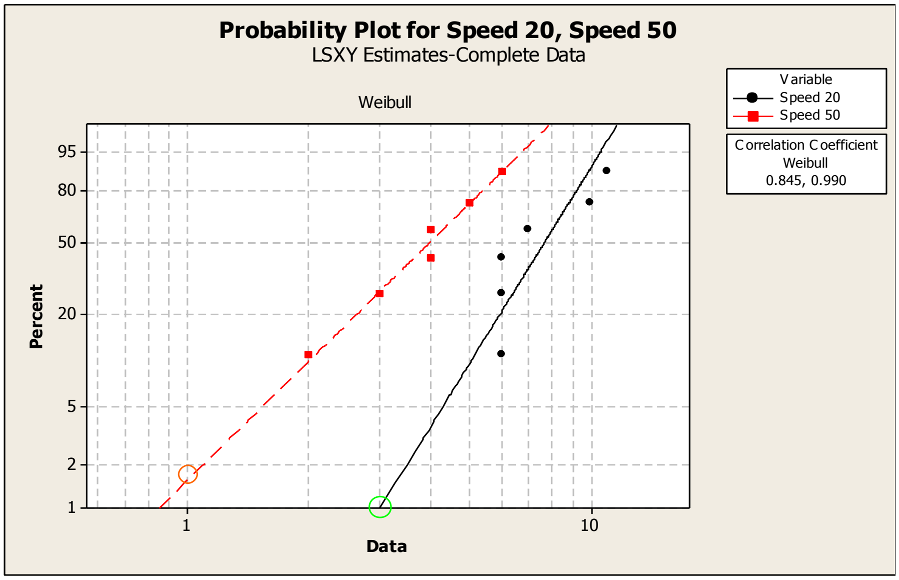


Figure 21: Weibull plot prediction for 2 cleaning speeds of 20 & 50 mm/sec using a WD setting (Wet-Dry cleaning). (Lot size: 83 panels).

On this experiment the cleaning speed result to be a key factor for the cleaning system using "WD" (Wet-Dry) and a slow speed (20 mm/sec). The replicate combination that has the higher prints without a bridge shows only 2 differences: Cleaner type & the Speed. Figure 22 & 23 illustrate the significant effect of both variables, where the speed has more weight than the cleaner type at this stage of the analysis.

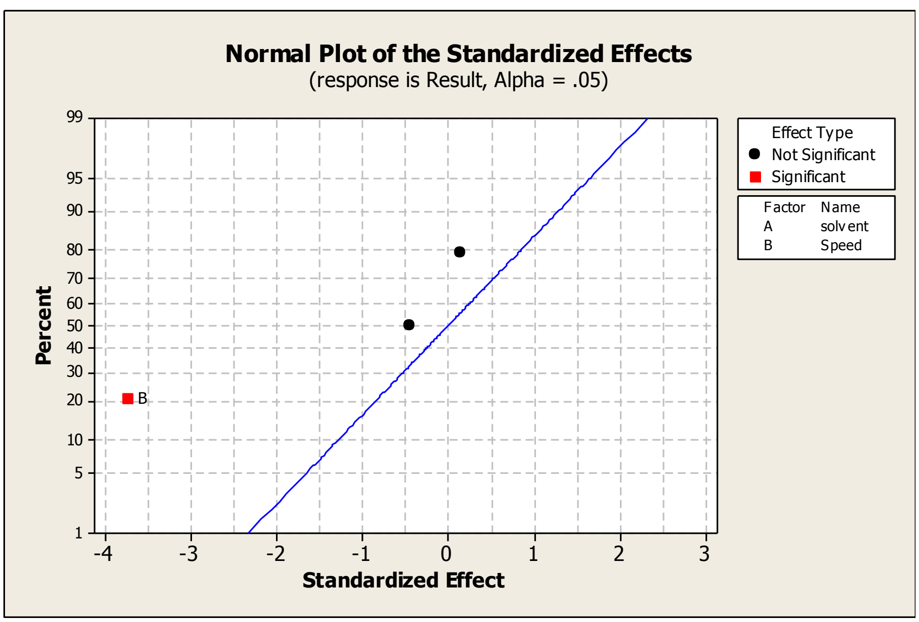


Figure 22: Significant effects: Cleaner & Speed: Speed (red square) its more distance form the blue line, while the black spots (A) represent the solvent used is not significant. (Lot size: 83 panels).

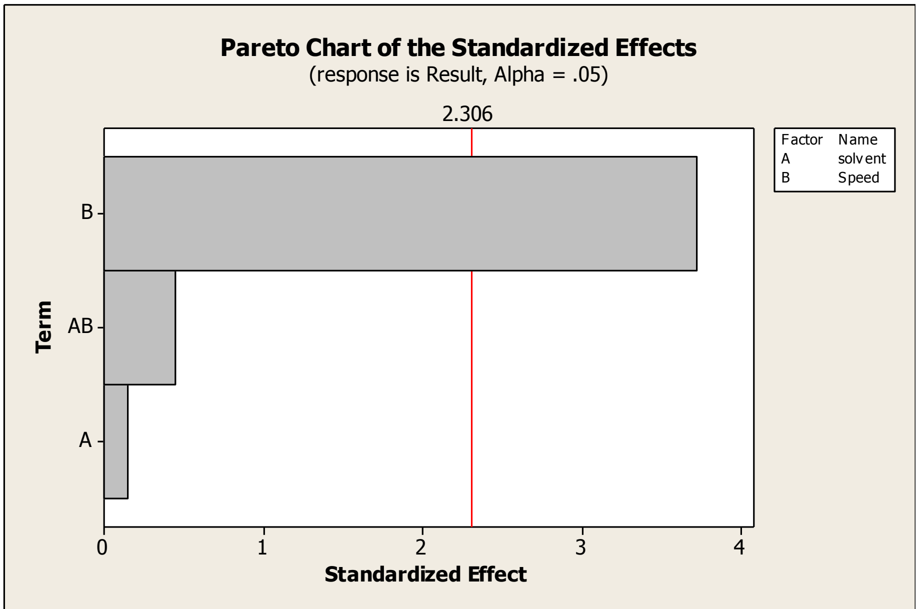


Figure 23: Main effects: Speed becomes more important in this stage of the experiment. (Lot size: 83 panels).

To double check the effect of the cleaners, a third experiment was set, following the entire lesson learned and changing only the cleaner type, the Transfer efficiency (TE) will be used to understand the differences.

Transfer Efficiency (TE) analysis:
The Transfer Efficiency (TE) performance was reviewed with what we know so far, using Nano coated stencil technology with the stencil opening design obtained for mass production and using regular production paste (power type 4, SAC 305, No clean). At this stage there is some definition of variables for the internal cyclone cleaning system; intention of this experiment was to compare only chemical performances between a water-base cleaner vs. IPA with the objective to improve process repeatability; the variables considered as noise were frozen in the same way as the last experiment.

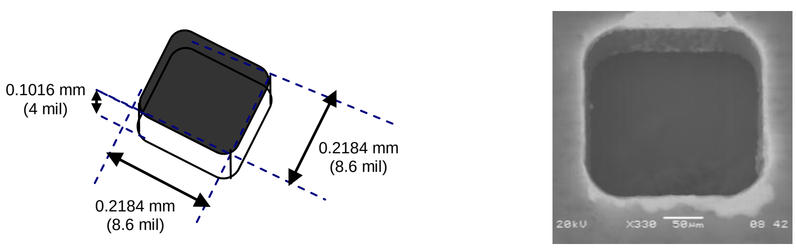


Figure 24: Stencil opening analyzed with the Nano coasted stencil.
(At the right side appears a SEM picture [stencil bottom side] with some damage on the Nano coating after 9 months of use).

Analyses made using the Nano coated stencil with opening of 0.2184 mm (8.6 mils) illustrated on Figure 24, the results shown a TE improves of almost 5% using the water base cleaner rather than the IPA (TE move it from 75.85% to 80.15% per pad). Using water base cleaner the printing performance shows more stable prints between panel´s. As comparison, the TE of the Nickel laser (opening of 0.2413 mm [9.5 mils] and square shape) was calculated and showed at right side of Figure 25. The “Sample mean” represent the volume variation between panels; the “sample of range” represent the volume variation between each pad of all CSP´s. Process out of control appear more frequently using the laser Nickel, Nano shown a process with less variation using water base cleaner; all 3 analysis are out of control.

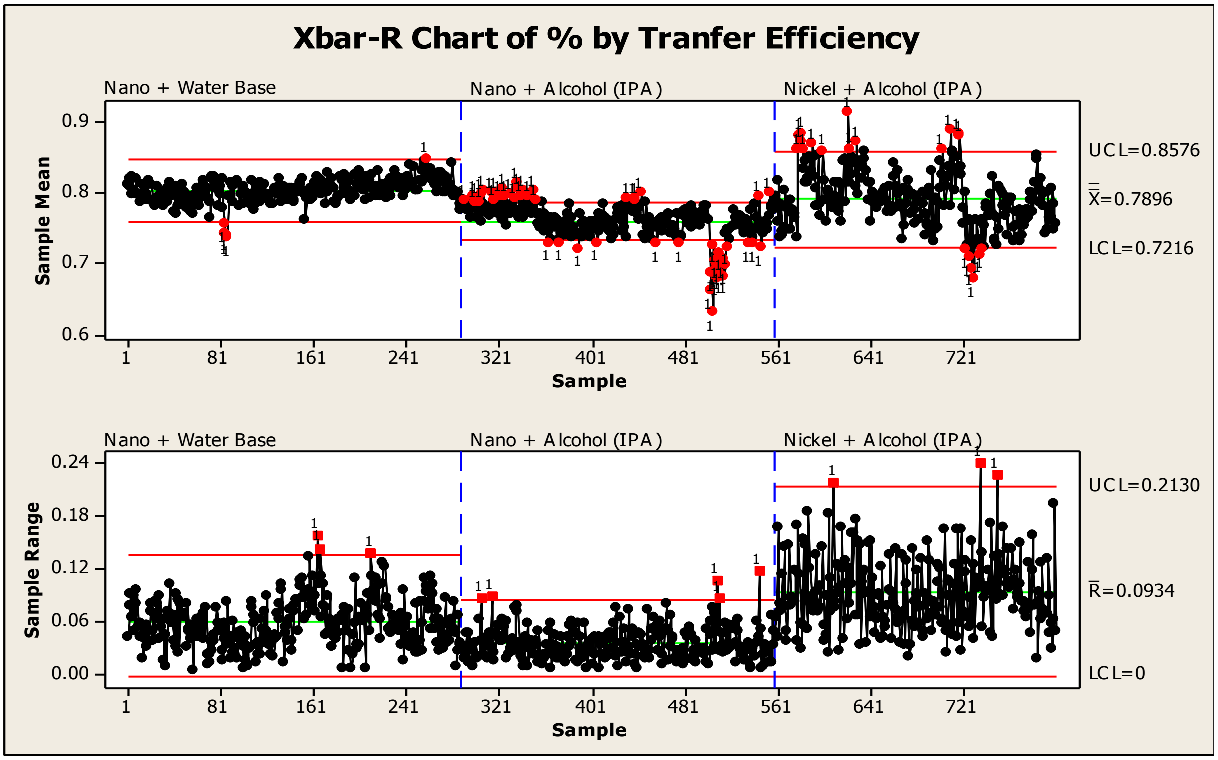


Figure 25: X bar charts used to compare “Transfer Efficiency” between Water & IPA using Nano (The Nickel laser cut use IPA as cleaner [lot size: 800 Panels, 3200 PCA´s]).

A “P” value was calculated to see if the two processes can be considered “different” (Figure 26). A “P” value close or lower than 0.05 ($P<0.05$) demonstrates that there is a significant difference on variation among the 2 cleaners. Less variation mean a more stable printing process.

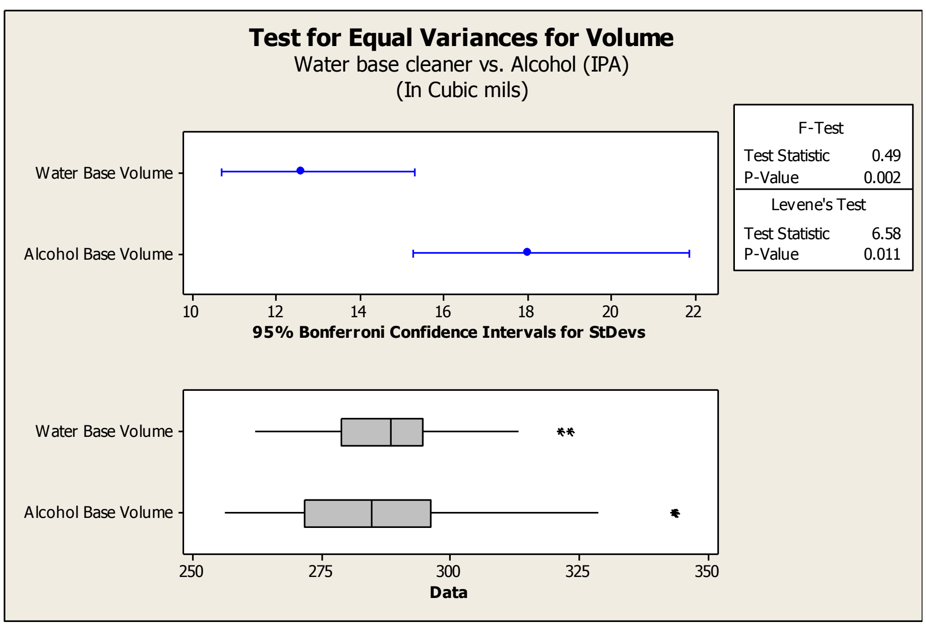


Figure 26: The test for equal Variance tells if the processes compared are similar or not: Water base cleaner demonstrate less dispersion of data (lot size: 557 panels = 2228 PCA´s).

Panel stretch / Pad Type Interaction:
Since the beginning of this study the objective it’s to improve printing process repeatability; based on this statement grow the need to understand some noises that may become uncontrollable variables in the long run. One of those silent variables is the

PCB & panel stretching. Some of the studies made on this path, found pads offset as much as 0.060 mm (2.39 mils), that affect the stencil gasketing for some mobile products (See Figure 27).

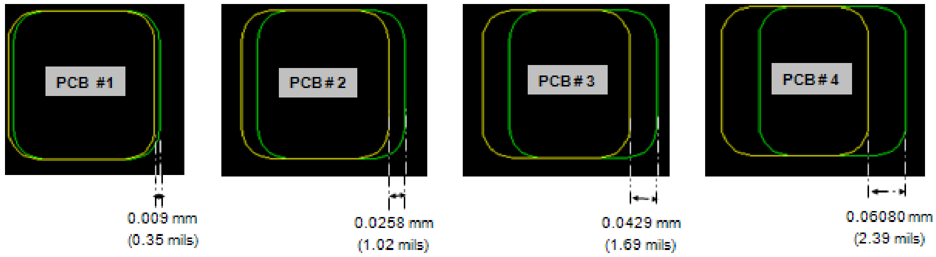


Figure 27: Measurements made on panels of 4X where the stretch increase along the panel. Stretching occurs mostly on the "X" axis rather than the "Y" axis.

In a second study the stretch move not only on the "X" axis, but also some movement on the "Y" axis is appreciate. In this second case the pads offset on the "X" axis was up to 0.0548 mm (2.131 mils) for images 4 (See Figure 28).

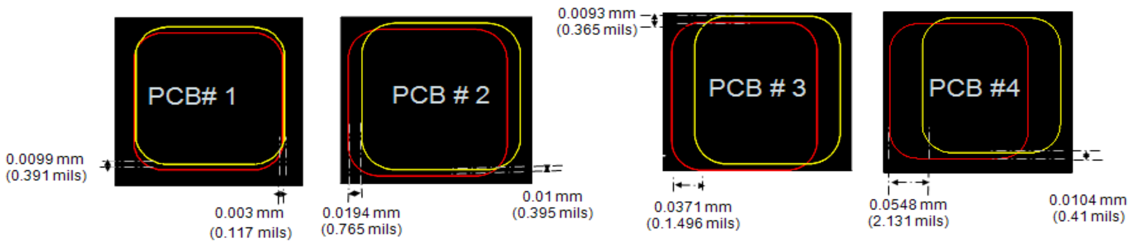


Figure 28: Measurements of the PCB stretch /Offset on a 4X panel

Beside the panel stretching, the copper pad over-each (that affects the original pad diameter) occurs often and has an important role in the PCB pad-stencil gasketing. As a consequence, the process repeatability is affected; pushing the ultra HVLM Mobile lines to clean every board in order to reduce bridges and poor printing performance. With the actual small amount of data per PCB supplier on board stretching, difficult the Gerber regeneration that may follow this offset behavior. Figure 29 represents the consciences of the panel / PCB stretching.

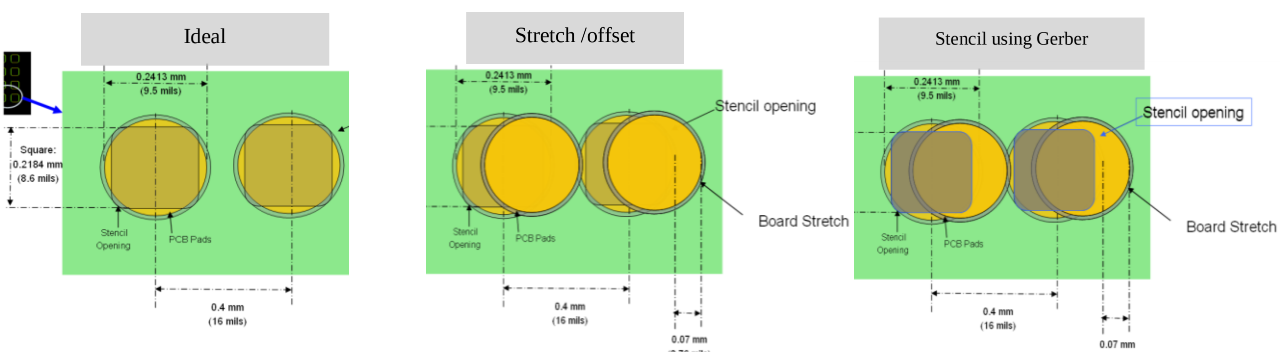


Figure 29: Stencils opening vs. PCB pad: represents the ideal world (CAD) and the consequences of the panel PCB stretch / offset.

The printing process under these conditions with a poor gasketing (seal between pad & stencil opening) become an issue, paste escape from the opening affecting not only the pitch but also the follow on printings, forcing the process to do a cleaning cycle after each print. (See figure 30).

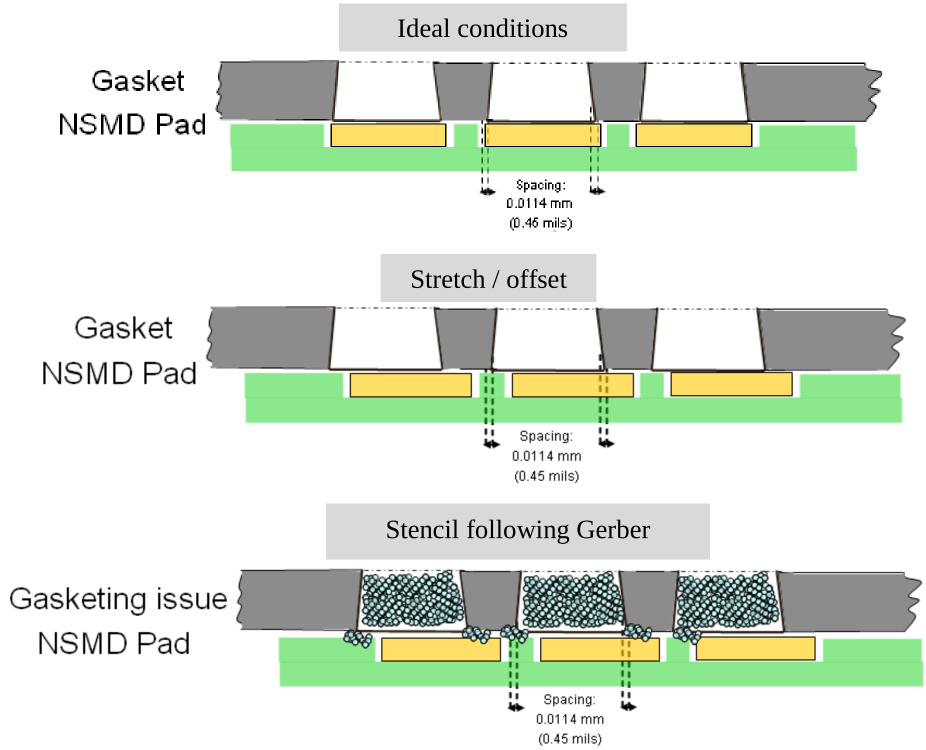


Figure 30: Gasketing issue between stencil & PCB pads.

Understanding printing performance by pad type:
Beside the uncontrollable variable of the PCB fabrication tolerance & panel stretch, we observe the need to comprehend the interaction of the type of pads we have in the CSP's of pitch of 0.4 mm. Pad with traces or inside a ground planes, SMD (solder mask define) & NSMD (non-solder mask define) are typical pad used by designers. The analysis made on this stage was the printing performance vs. pad shape, figure 31 illustrates the land patterns of the pads of 2 identical CSP's from the same board in a 4X panel array. Table 6 illustrated the pad categories made & the % of each type.

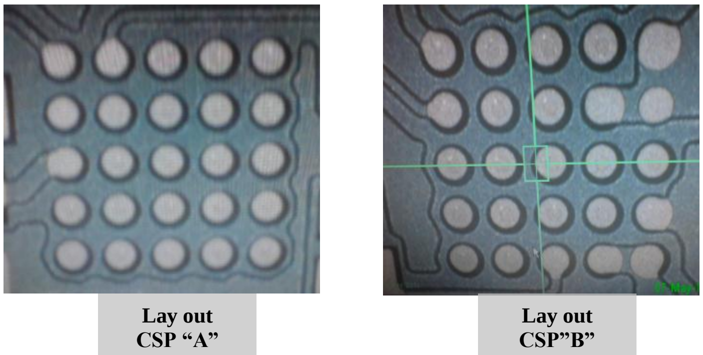
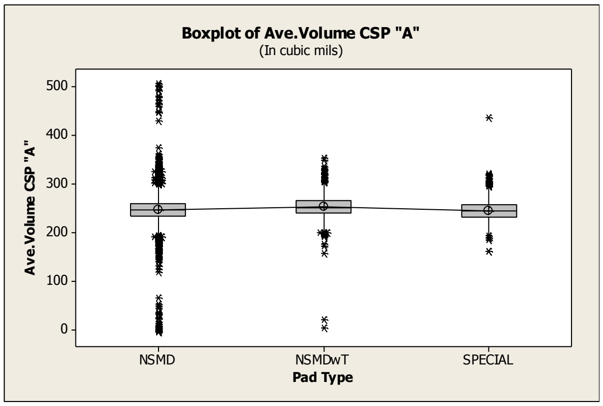


Figure 31: Close up of the pad land pattern for two 0.4 mm pitch CSP's.

Table 6: Categories of pad type´s for the 2 "identical" CSP's of pitch of 0.4 mm

Type of pad	*CSP "A"*	*% of type of pad*	*CSP "B"*	*% of type of pad*
NSMD	22	88%	16	64%
SMD	2	8%	2	12%
NSMD with trace	0	0%	3	8%
Special	1	4%	4	16%
Total of pads	**25**	100%	**25**	100%

The impact of the pad type with the panel / PCB stretch was analyzed using a sample of 298 panels (1192 PCA's), settings used where the best found so far: WD with cleaning speed of 20 mm/sec & water base cleaner, cleaning was every 2 prints. Paste volume performance by pad type can be appreciated for both CSP's in Figure 32. The NSMD pads on both cases become more sensitive to the pad-stencil gasketing due to the lower area of the NSMD pad.



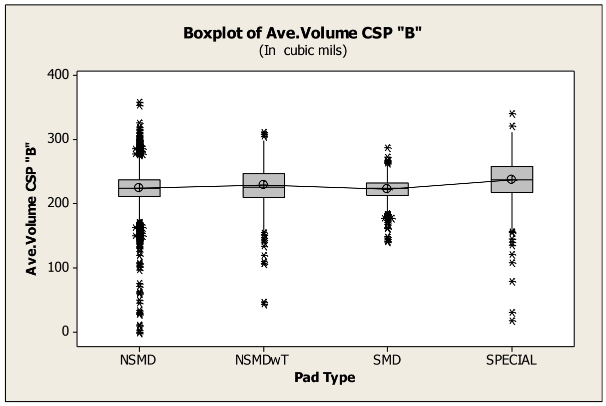
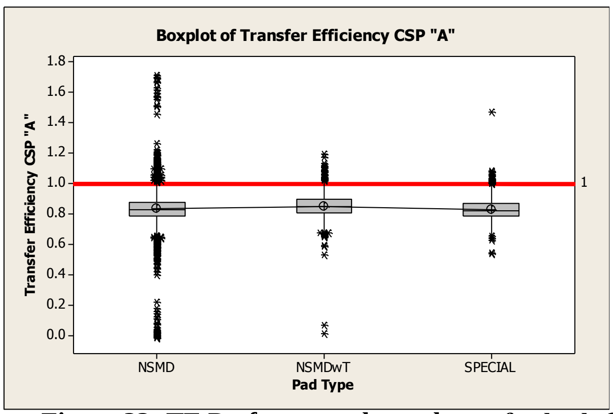


Figure 32: Paste volume deposit performance by pad type of CSP "A" & "B". (Sample size: 298 panels)

Transfer efficiency comparison between pad types was analyzed and can be appreciate at Figure 33 (the red line indicates ideal 100 % of TE). It is revealed in higher transfer efficiencies (in the cases where the data obtained is greater than 100%) a trend of stencil contamination is present that causes bridging. The phenomenon mechanism indicates paste escapes from previous print reducing the pitch & affecting the shape of the paste deposit.



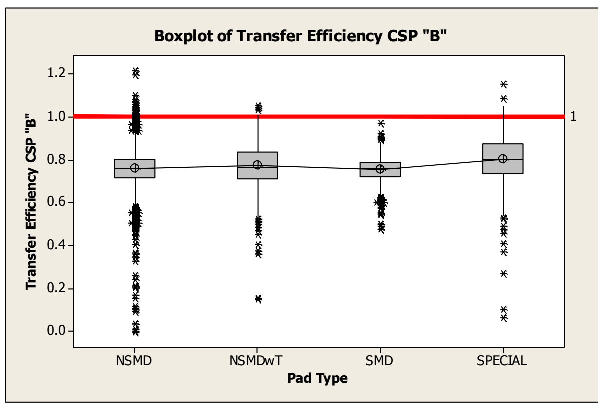


Figure 33: TE Performance by pad type for both CSP's of pitch of 0.4 mm. (Sample size: 298 panels)

Transfer efficiency (TE) Interaction with the panel was also evaluated to see the stretch impact; being in the case of CSP "A" (with 88% of NSMD pads) the most sensitive on this non controllable variable (Figure 34).

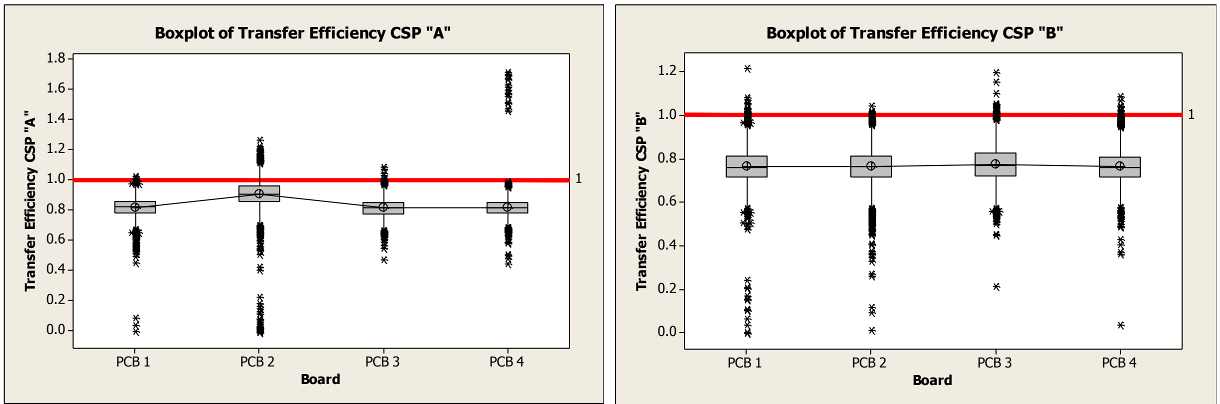


Figure 34: TE Performance by image of the panel of 4X, the CSP "A" with 88% of NSMD becomes the most sensitive. (Sample size: 298 panels)

The analyses of variance between CSP´s vs. Panel are appreciated on Figure 35, in both cases the stretching causes gasketing issues, but at CSP "A" (with 88% of NSMD pads) becomes more unstable against panel stretching.

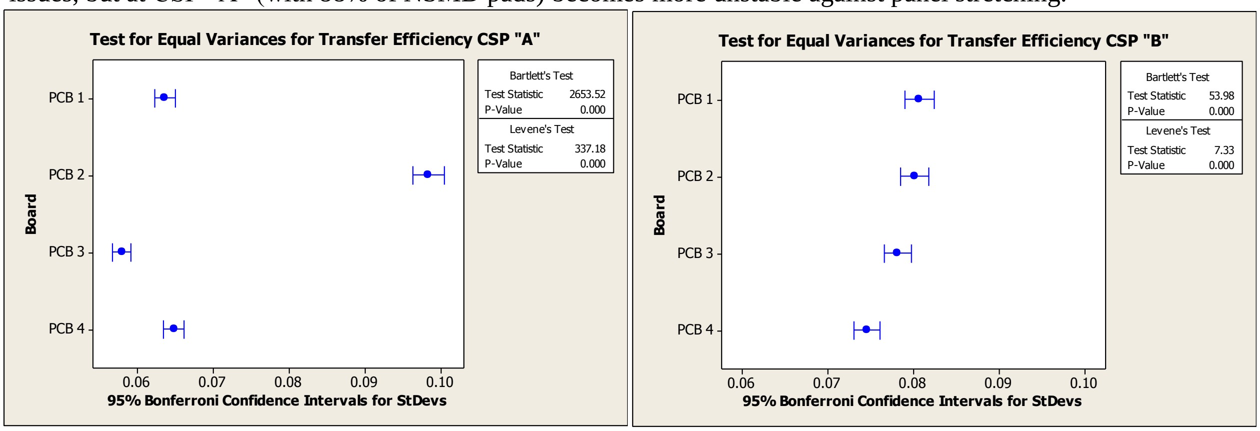


Figure 35: TE variance vs. images of the panel by type of component (Sample size: 298 panels).

Cleaning settings Vs Printing Settings:

Now following the path learned so far, surge the need to comprehend the interaction of cleaning variables against printing variables. A DoE was defined in order to reduce the print variability and increase the cleaning frequency to at least every two boards to save seconds and improve printing cycle time. From previous experiments & lessons learned, we take 5 variables with 2 levels. The DoE generates 18 run and 16 panels per combination were required (See table 7). In total 288 panels (1152 boards) were measure it.

All data was capture using and automatic SPI in line. Note: the "Cyclone" cleaning system was used in all the experiments (with the oscillation option "On" for Wet and "Dry" and "Off" for vacuum) and cleaning was made every two prints.

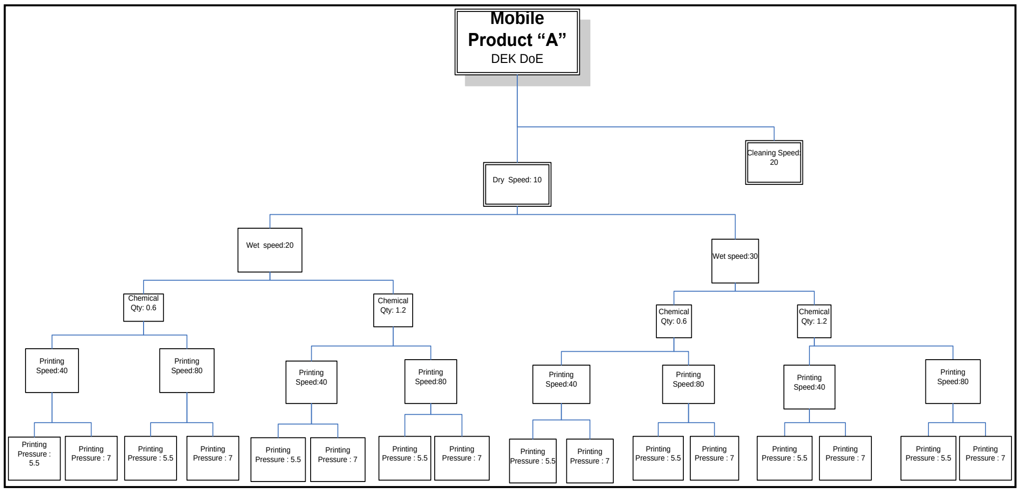


Figure 36: FRD (Factor Randomization Diagram) for one of the two DoE ramification.

Table 7: DoE runs with variables & blocks

Block	StdOrder	RunOrder	CenterPt	Blocks	Dry Speed (mm/sec)	Vacuum Speed (mm/sec)	Chemical Qty (seconds)	Printing Speed (mm/Sec)	Printing Pressure (Kg/Cm2)	WET Speed (mm/sec)
WVD	3	1	1	1	10	30	0.6	40	7	40
WVD	6	2	1	1	20	20	1.2	40	7	40
WVD	1	3	1	1	10	20	0.6	80	7	40
WVD	9	4	0	1	15	25	0.9	60	6.25	40
WVD	5	5	1	1	10	20	1.2	80	5.5	40
WVD	7	6	1	1	10	30	1.2	40	5.5	40
WVD	4	7	1	1	20	30	0.6	80	5.5	40
WVD	8	8	1	1	20	30	1.2	80	7	40
WVD	2	9	1	1	20	20	0.6	40	5.5	40
WD	16	10	1	2	10	30	1.2	40	5.5	40
WD	11	11	1	2	20	20	0.6	40	5.5	40
WD	17	12	1	2	20	30	1.2	80	7	40
WD	12	13	1	2	10	30	0.6	40	7	40
WD	15	14	1	2	20	20	1.2	40	7	40
WD	14	15	1	2	10	20	1.2	80	5.5	40
WD	18	16	0	2	15	25	0.9	60	6.25	40
WD	10	17	1	2	10	20	0.6	80	7	40
WD	13	18	1	2	20	30	0.6	80	5.5	40

The paste height was the value analyzed in the DoE, due change in shape deposit affected greatly the printing performance with insufficiencies or bridges. All data used in the graphs are the Standard deviation of the paste height; this parameter will let us know in a quick manner an out of control process condition and may create prevention systems rather than a contention type.

The results from the runs (standard deviation of the paste height) were graph on Figure 37. Each run are shown on the "X" axis; standard deviation it´s on the "Y" axis. Lower the standard deviation mean less variation in the paste height among all pads, this represents more uniformity and is one of the behaviors we are looking for. Runs 1, 4, 6, 11, 12, 13 and 14 become the ones with lower variation.

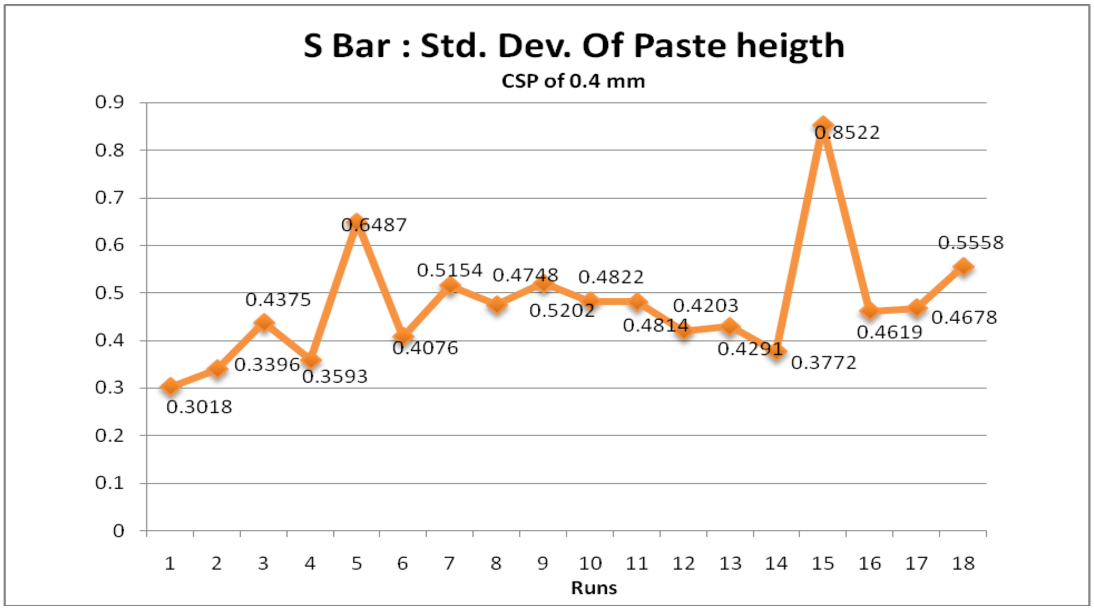


Figure 37: Standard deviation of the paste height by every DoE Run (in mils), sample size: 1152 boards (Lower values obtained are in the range of 0.3018 to 0.3772).

The Main effect behavior of the DoE variables can be appreciated at figure 38. The "Y" axis it's the standard deviation (Std. Dev.) of the paste height. Here lower the value on the Y axis, less paste height variation and more process repeatability.

The lines plotted with higher angles represent a variable with more weight or importance in the outcome; main variables were the printing speed & printing pressure.

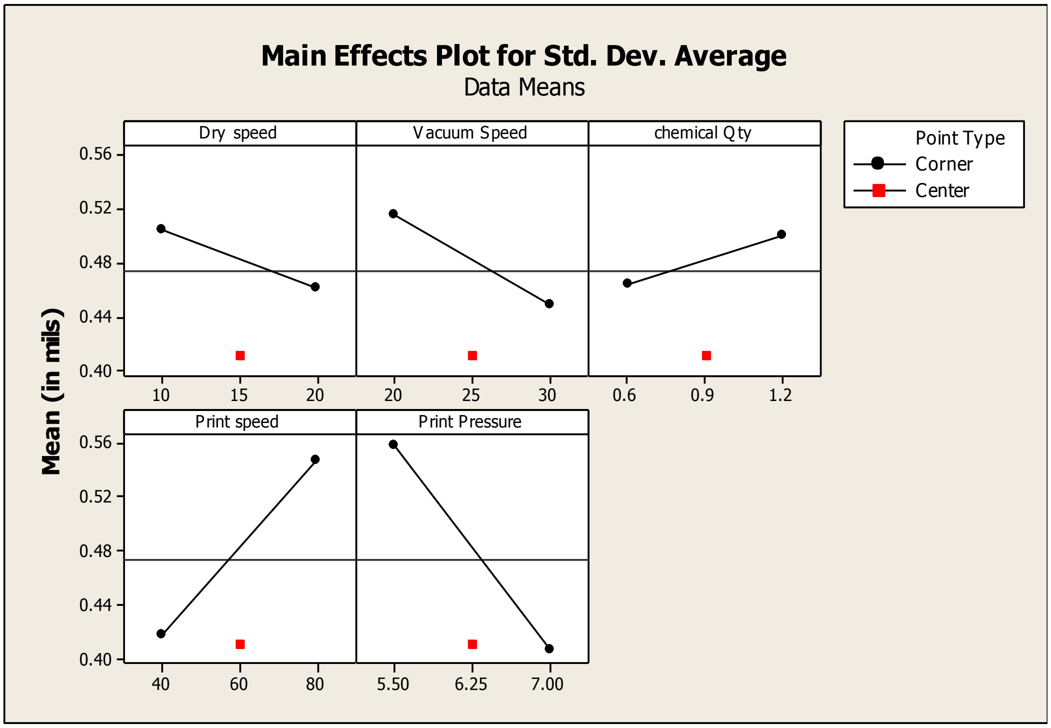


Figure 38: Main effect behavior of the DoE: Printing variables Vs Cleaning Variables.

From the t-test analysis the main "terms" or variables of the model are explained. The "P" value indicated if a term is significant or not significant (lower P value indicate more significance). Here the center point or curvature result non significant; however the "block" variable have more weight on the behavior. These factors under the model explain the 79.27% of the entire experiment variation.

Factorial Fit: Std. Dev. Av versus Block, Dry speed, Vacuum Speed.....

Estimated Effects and Coefficients for Std. Dev. Average (coded units)

Term	**Effect**	**Coef**	**SE Coef**	**T**	**P**
Constant		0.48198	0.01422	33.90	0.000
Block		-0.02906	0.01341	-2.17	0.062
Dry speed	-0.04278	-0.02139	0.01422	-1.50	0.171
Vacuum Speed	-0.06720	-0.03360	0.01422	-2.36	0.046
Chemical Qty	0.03670	0.01835	0.01422	1.29	0.233
Print speed	0.12917	0.06459	0.01422	4.54	0.002
Print Pressure	-0.15193	-0.07596	0.01422	-5.34	0.001
Vacuum Speed*chemical Qty	-0.04100	-0.02050	0.01422	-1.44	0.187
Vacuum Speed*Print Pressure	0.06818	0.03409	0.01422	2.40	0.043
Ct Pt		-0.07138	0.04266	-1.67	0.133

S = 0.0568754   PRESS = *
R-Sq = 90.25%   R-Sq(pred) = *%   R-Sq(adj) = 79.27%

The factors that statistically have more weight are illustrated in Figure 39; print speed followed by Print pressure get priorities number 1&2; the interaction of vacuum /print pressure and Vacuum get priorities 3&4.

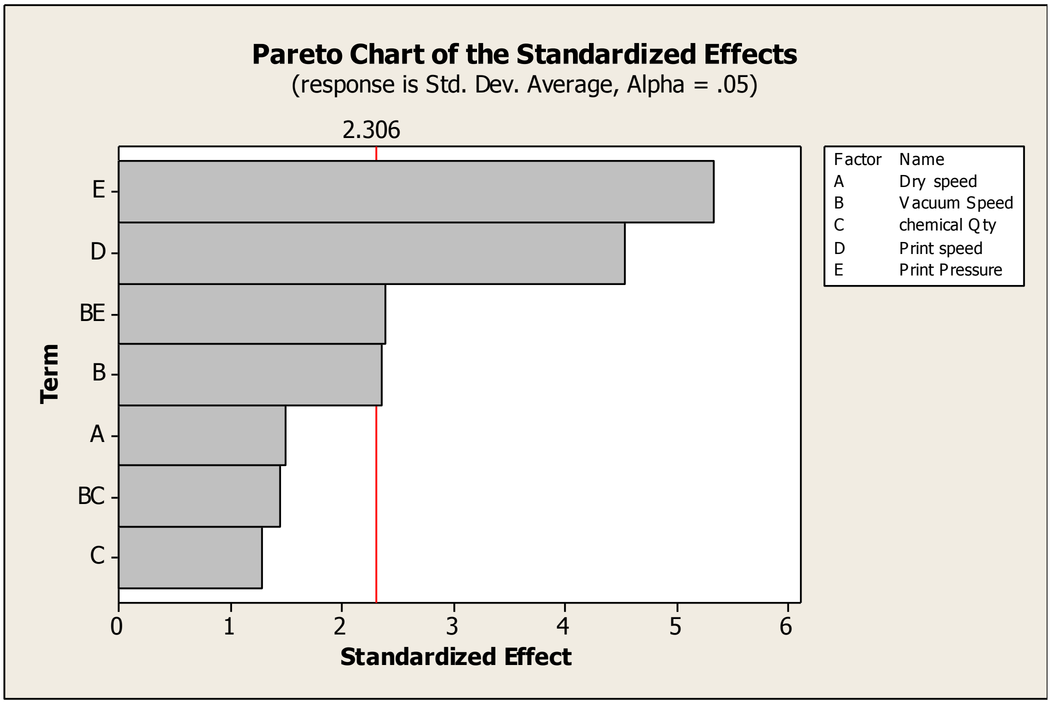


Figure 39: More important factor that affects the printing performance & process repeatability.

The cube plot (figure 40) demonstrates in a clearly manner how to obtain the lowest variation of the paste height (lowest Std.Dev. 0f 0.35840), that is reach on the corner point with a print pressure of 7 kg/cm^2, print speed of 40 mm/sec and with a dry speed set at 20 mm/sec.

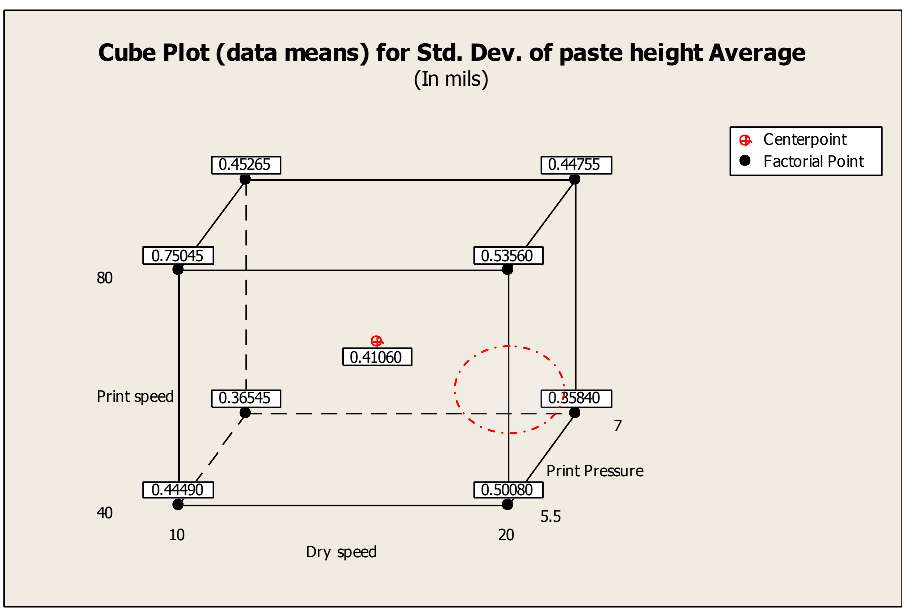


Figure 40 illustrates the variables interaction in a cube plot, the lowest standard deviation is 0.3540. (Sample size: 1152 boards).

One of the parts of the DoE was the "blocks": WVD & WD, one way to understand the differences between those two are the box plots graphs. At Figure 41 the interaction of the blocks can be appreciated; somehow the vacuum become important due to affect the paste deposit for the next print; the combination WVD (Wet-Vacuum-Dry) has more dispersions than the WD (Wet-Dry). From same graph the best settings are equal in printing speed and print pressure than the cube plot graph from above.

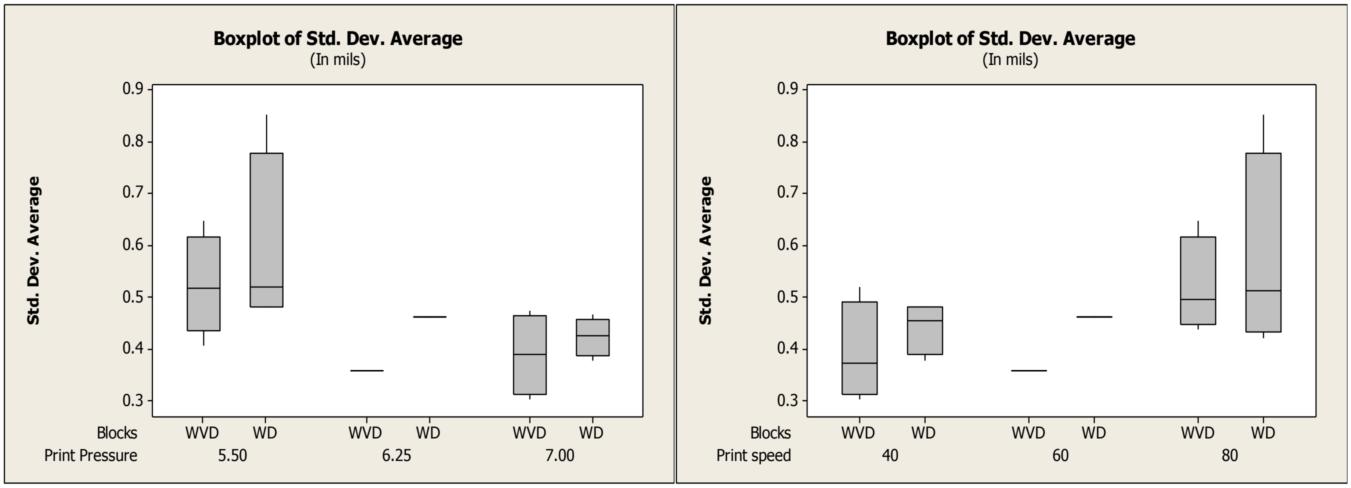
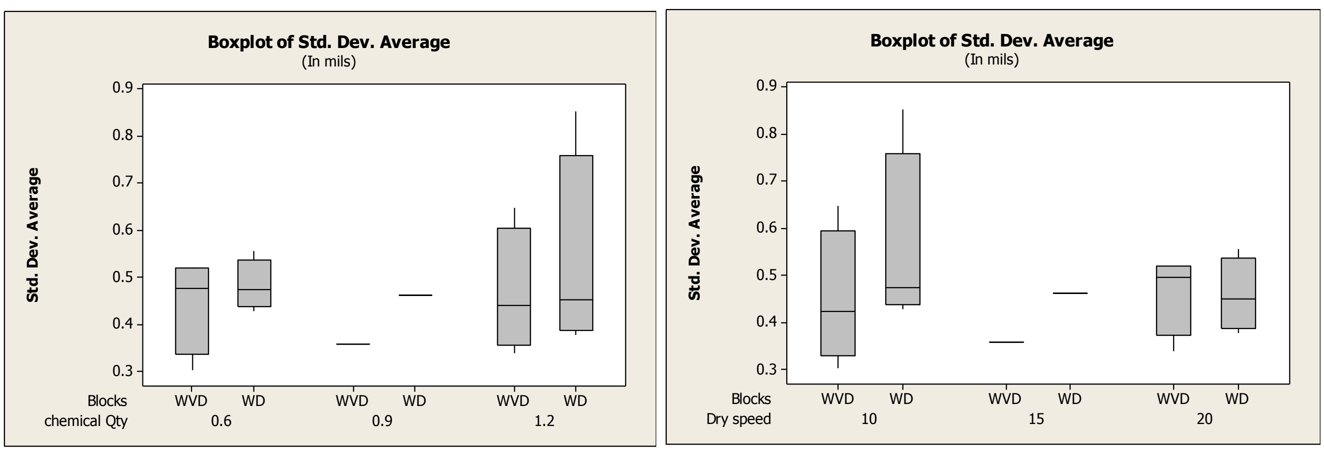


Figure 41: DoE Block behavior: WVD vs. WD: Print pressure & Print speed (sample size: 1152 boards).

Block of WD (Wet-Dry) had demonstrated a less dispersion in the standard deviation of the paste height (Figure 42). For both blocks to obtain less variation the amount of cleaner (chemical quantity) is with the pump "On" for 0.6seconds. For the Dry speed, 20 mm/ sec gets the lowest variation for both blocks. Best setting so far can be read at table 8.

Figure 42: DoE Block behavior: WVD vs. WD: Chemical quantity & Cleaning Dry speed. (Sample size: 1152 boards).



From the DoE results we can obtain the following best settings:

Table 8: DoE best settings obtain from the 18 runs.

Parameters	Better Settings found from DoE
Print Speed	**40 mm/sec**
Paste Pressure	**7 Kg/cm2**
Chemical Quantity	**0.6 seconds**
Cleaning Dry Speed	**20 mm/sec**
Best block:	**WD**
Cleaning Wet speed [frozen] :	**40 mm/sec**
Print Gap (mm) [frozen] :	**0**
Temperature (°C) [frozen] :	**25**
Humidity (% RH) [frozen] :	**38.5%**
Cleaning system [frozen]:	**Cyclone ("On" for Wet & Dry)**
Cleaner [frozen]:	**Water Base**

Stencil opening interaction:
Based on the previous results another effort made to improve printing stability through time was to try to improve the stencil gasketing. In the case of having a small stencil opening, the stretching somehow can be absorbed by the space left on the side of the pad. The performance of smaller stencil openings was analyzed with 8 different designs; to understand the impact of the paste viscosity in the Transfer Efficiency (TE) the temperature was considered as a key factor. In total 192 panels was analyzed at 3 different temperatures: 22, 25 & 27.5 ºC. Experiment combination can be seen at table 9. The proportion of PCB pads vs. Stencil design opening can be appreciate at figure 43. Of course a Nano stencil was used with parameters from table 8.

Table 9: Stencil designs & temperatures analyzed.

Stencil design #	Stencil opening (X by Y)	**Panels run at Temperature** 22 ºC	**Panels run at Temperature** 25 ºC	**Panels run at Temperature** 27.5 ºC
1	0.218 X 0.218 mm (8.6 X 8.6mils)	8	8	8
2	0.213 X 0.213 mm (8.4 X 8.4 mils)	8	8	8
3	0.208 X 0.208 mm (8.2 X 8.2 mils)	8	8	8
4	0.203 X 0.203 mm (8.0 X 8.0 mils)	8	8	8
5	0.198 X 0.198 mm (7.8 X 87.8 mils)	8	8	8
6	0.193 X 0.193 mm (7.6 X 7.6 mils)	8	8	8
7	0.188 X 0.188 mm (7.4 X 7.4 mils)	8	8	8
8	0.183 X 0.183 mm (7.2 X 7.2 mils)	8	8	8
Note:	Square opening / round corner with radius of: 0.0388mm (1.528 mils); sample size: 192 panels			

In this experiment 3 components were affected with the apertures per board in a 4X panel array (All 0.4 mm pitch CSP's). In total 576 components were affected in the runs. Stretching impact cannot be appreciated due to each design affect only 1 board of the panel.

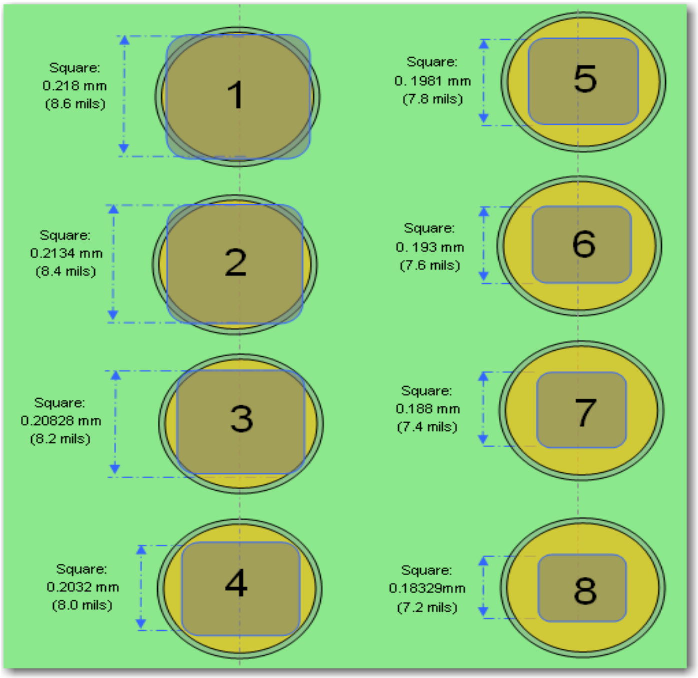


Figure 43: Different stencil designs analyzed (one per each board, on a stencil with double image).

Volume was measured considering temperature and stencil design. Result of the transfer efficiency (TE´s) of each design is presented at table 10, where the area & aspect ratio is also calculated. Expected TE values are from 70 to 75%, excellent results are around 75% to 85% but not greater than 100% (as we saw on Figure 30 & 31). TE´s bellow 70% (in red) represent not acceptable values.

Table 10: Stencil design printing performance measuring TE vs. Temperature (sample size: 192 boards)

Stencil opening design	Width "Y"	Length "X"	Stencil thickness	Aspect Ratio	Area Ratio	Theoretical Volume	TE at 22 ºC	TE at 25 ºC	TE at 27.5 ºC
1	**0.218 mm (8.6 mils)**	**0. 218 mm (8.6mils)**	**0.101 mm (4 mils)**	**2.15**	**0.5375**	**4.799 E-3 mm^3 (295.84 $mils^3$)**	**80.648**	**80.533**	**84.056**
2	**0.213 mm (8.4 mils)**	**00.213 mm (8.4 mils)**	**0.101 mm (4 mils)**	**2.1**	**0.525**	**4.582 E-3 mm^3 (282.24 $mils^3$)**	**80.010**	**73.601**	**70.058**
3	**0.208 mm (8.2 mils)**	**0.208 mm (8.2 mils)**	**0.101 mm (4 mils)**	**2.05**	**0.5125**	**4.369 E-3 mm^3 (268.96 $mils^3$)**	**81.752**	**71.975**	**71.758**
4	**0.203 mm (8.0 mils)**	**0.203 mm (8.0 mils)**	**0.101 mm (4 mils)**	**2**	**0.5**	**4.162 E-3 mm^3 (256 $mils^3$)**	**81.516**	**71.559**	**69.139**
5	**0.198 mm (87.8 mils)**	**0.198 mm (87.8 mils)**	**0.101 mm (4 mils)**	**1.95**	**0.4875**	**3.959 E-3 mm^3 (243.36 $mils^3$)**	**78.049**	**64.204**	**67.357**
6	**0.193 mm (7.6 mils)**	**0.193 mm (7.6 mils)**	**0.101 mm (4 mils)**	**1.9**	**0.475**	**3.762 E-3 mm^3 (231.04 $mils^3$)**	**76.398**	**59.664**	**57.545**
7	**0.188 mm (7.4 mils)**	**0.188 mm (7.4 mils)**	**0.101 mm (4 mils)**	**1.85**	**0.4625**	**3.569 E-3 mm^3 (219.04 $mils^3$)**	**80.141**	**58.322**	**57.393**
8	**0.183 mm (7.2 mils)**	**0.183 mm (7.2 mils)**	**0.101 mm (4 mils)**	**1.8**	**0.45**	**3.382 E-3 mm^3 (207.36 $mils^3$)**	**78.014**	**54.682**	**53.160**

Figure 44 shows the transfer efficiency behavior; TE at 22ºC has the lowest dispersion and the highest transfer efficiency for all the stencil openings. It's seems like coalesce between paste solder balls with a thicker flux (due the lower temperature) keep them together and the release was more uniform between each CSP pads, other possible explanation is that coalescence forces among each solder balls was greater than the stencil opening retention forces. Snap off settings for all runs were at speed of 1mm/sec for a separation of 1 mm.

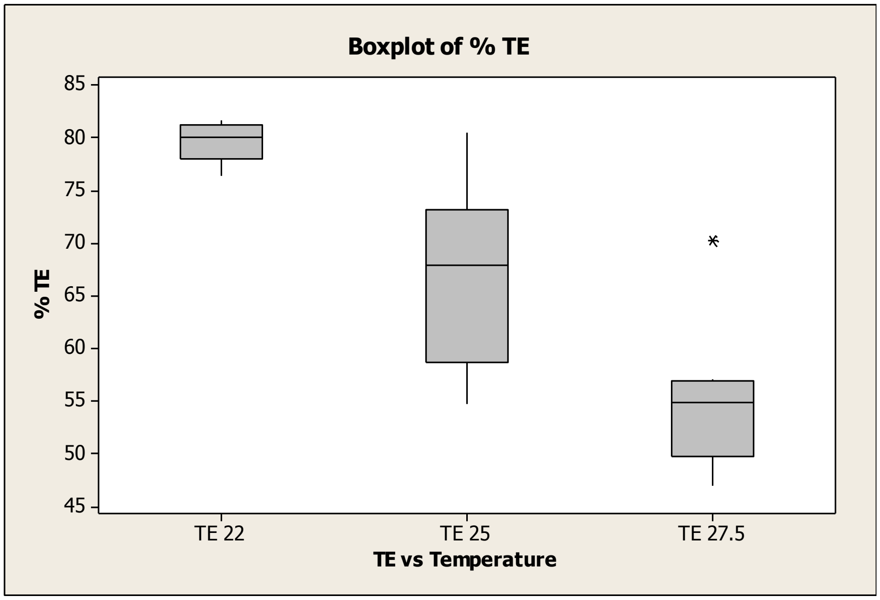


Figure 44: Transfer efficiency performance vs. temperature using all the stencil openings (sample size: 192 panels)

A test for equal variance demonstrates the dispersion of the TE´s at the 3 temperatures, (low P values represent significant differences in this matter). Same low dispersion of data can be appreciated at 22º C. (See Figure 45). Temperature plays a very important role and further analyses are required to see if in the long runs this behavior prevails.

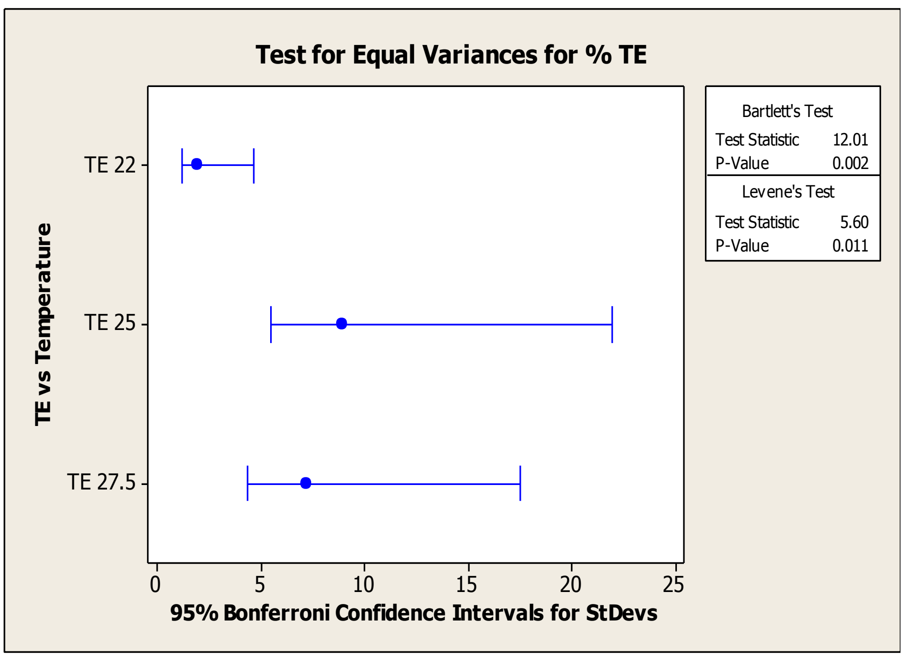


Figure 45: Transfer efficiency test for equal variance for all stencil openings. (Sample size: 192 panels)

The Area ratio gives you and idea of how good the paste releases from stencil, as a references regular value must be above >0.66 for laser cut stencils. The IPC studies mention that for E-Fab stencil value can go down to >0.5. As shows on table 10 each stencil design produced an aspect & area ratio that affect the printing performance which can be measure by the transfer efficiency (TE), an standard values for these types of components are in the order of 70-75%.

The results that combine both parameters are in the scatter plot of figure 46, which show that at 22ºC the change in the area ratio almost not affect the transfer efficiency. At temperatures of 25ºC the TE 70% threshold is around an area ratio of 0.5; the performance at 27.5ºC was particularly unstable to come up with some conclusions.

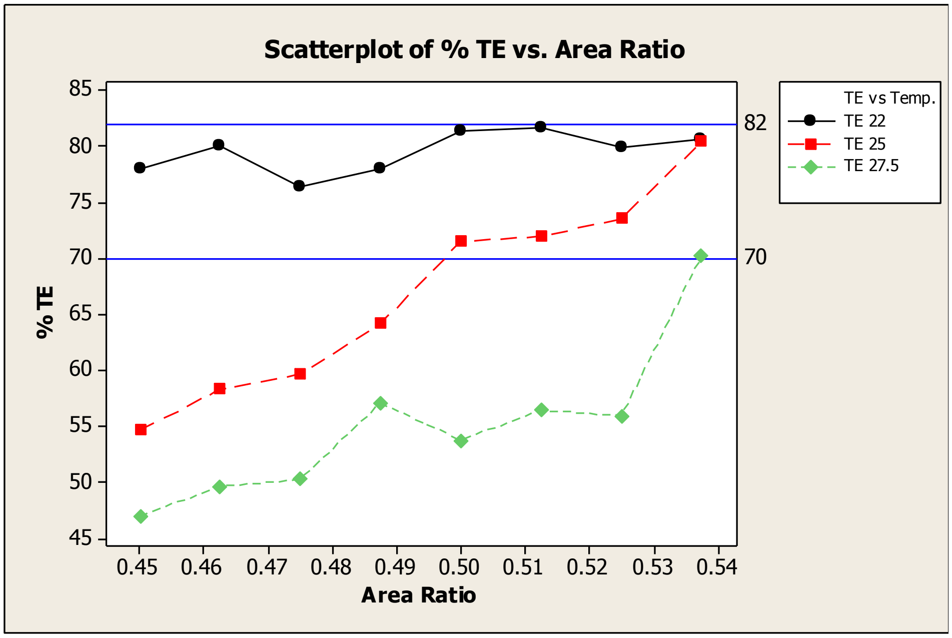


Figure 46: TE vs. Area ratio performance by Temperature (sample size: 192 panels).

The stencil design # 3 has the lowest temperature impact due to in the 3 temperature levels, shows TE values above 70%. To verify it 1 shift of production boards were analyzed using an stencil with square opening of 0.208 mm (8.2 mils) in all the 0.4 mm pitch CSP´s, some special tracking was establish to segregate type of failures, the data was compared with the actual stencil design (square of 0.236 mm [9.3 mils]), results are at table 11.

Table 11: DPPM´s per stencil opening in a shift run

Stencil design	Units ran (PCA´s)	# of CSP's affected by stencil design	# of Failures	DPPM´s
Square 0.236 mm (9.3 mils)	2615	10	24	91,743.12
Square 0.208 mm (8.2 mils)	2615	10	2	7,645.26

Note: Square stencil opening of 0.236mm (9.3 mils) is a customer request (Sample size: 2615 PCA´s)

Conclusions:

1. More stable volume & less paste height variation were obtained using the Nano stencil in comparison with E-Fab & Nickel laser cut.

2. Transfer efficiency is significantly better using Nano coated when compared with the other type of stencil technologies.

3. Greater transfer efficiencies are obtained using the Nano stencil with water base cleaner rather than IPA with identical settings.

4. Interaction between panel stretches with the type of pad affecting the print stability. The pad with the poorest repeatability was the NSMD, which affect more the gasketing.

5. From the DoE the best combinations that reduce variability between print settings vs. clean settings were as follow:
   - Print speed and print pressure result as main variables in the print repeatability: speed of 40 mm/sec with print pressure of 7 kg/cm2 produce the less variation in paste height between each pad printed over the 0.4 mm pitch CSP's.

- The cleaning settings play a key role to process stability. The combination WD works better than the WVD with a Dry speed of 20 mm/sec and wet speed of 40 mm/sec.

6. Transfer efficiency is greatly affected by the screen printer temperature; best transfer efficiencies were obtained at 22ºC; however further experiments are required to demonstrate stability in a long period of time.

7. It is recommended to use the Nano coated stencil for the fine pitch device and the smaller aperture for the better paste release to avoid insufficient solder (better TE) as well as the solder bridging (small aperture).

Observations:

- Production noise should be under control for optimizing the Nano stencil technology.
- Stencil house should also study and reduce their noise for consistent output.

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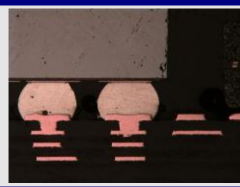
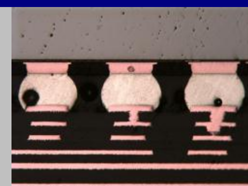
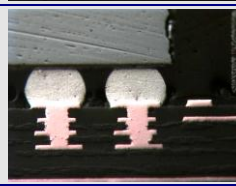
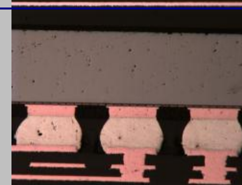
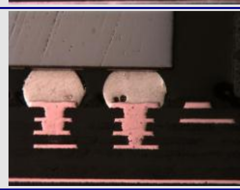
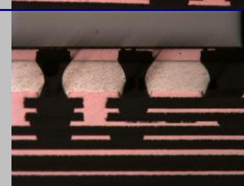
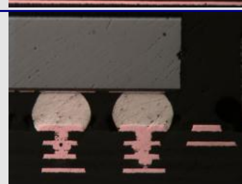
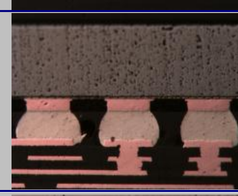
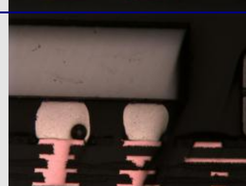
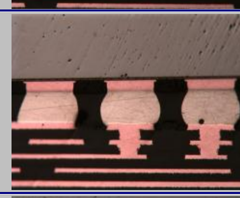
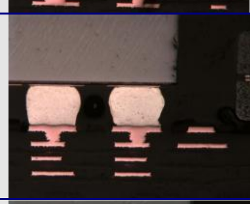
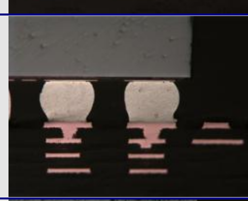
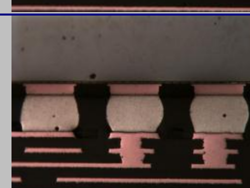
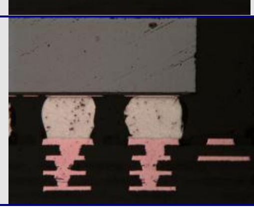
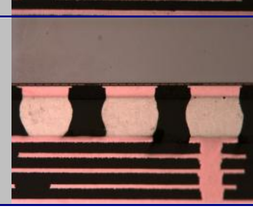
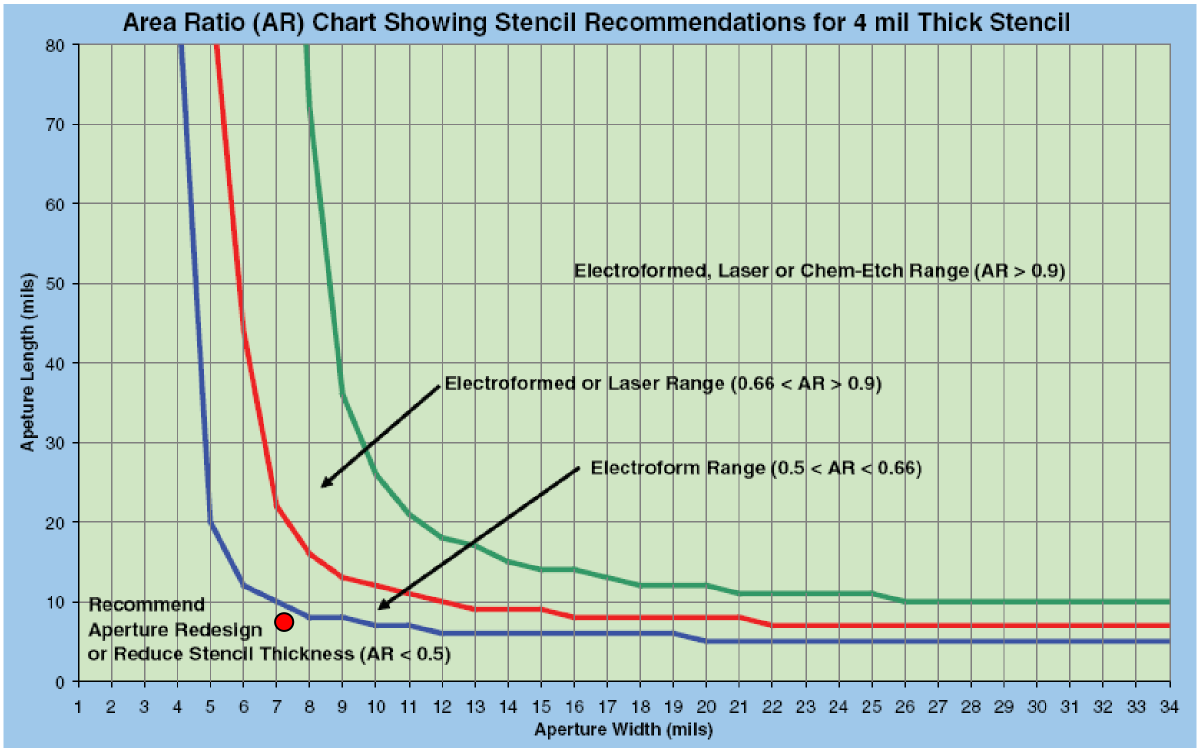
Appendix:

1) Cross section table of the different stencil apertures, units ran at 25ºC (images & % data shown as references only), more analysis are require to determine the adequate stencil opening.

Stencil Design	**Stencil opening**	**Cross section CSP "A"**	**Cross section CSP "B"**	**Max. Void %**	**% Negative wetting**
1	**0.218 X 0.218 mm (8.6 X 8.6mils)**			**40.8**	**0**
2	**0.213 X 0.213 mm (8.4 X 8.4 mils)**			**10.2**	**8.5**
3	**0.208 X 0.208 mm (8.2 X 8.2 mils)**			**28.6**	**0**
4	**0.203 X 0.203 mm (8.0 X 8.0 mils)**			**24.2**	**0**
5	**0. 198 X 0.198 mm (7.8 X 87.8 mils)**			**28.2**	**21.3**
6	**0.193 X 0.193 mm (7.6 X 7.6 mils)**			**24.8**	**20.3**
7	**0.188 X 0.188 mm (7.4 X 7.4 mils)**			**14.1**	**16.7**
8	**0.183 X 0.183 mm (7.2 X 7.2 mils)**			**0**	**53.4**

2) Image from IPC-7525 regarding Area ratio.



References

[1] Carmina Läntzsch, Alexander University Erlangen, "Characteristics and Potentials of Nano-Coated Stencils for Stencil Printing Optimization", SMTA 2010.

[2] IPC-7525, Stencil Design Guidelines.

[3] Donald J. Wheeler; David S. Chambers "Understanding statistical process control".